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PROCEEDINGS OF THE LONDON CONFERENCE ON OPTICAL INSTRUMENTS

Held at the Imperial College, London, S.W.7

19–26 July, 1950

PROCEEDINGS OF THE LONDON CONFERENCE ON OPTICAL INSTRUMENTS 1950

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FOREWORD

At its second meeting, held in Delft, July, 1948, the International Optical Commission accepted an invitation from the British Delegation to hold its next meeting in London in July, 1950. The International Optical Commission is a branch of the International Union of Pure and Applied Physics and its focal point in Great Britain is the British Sub-Committee for Optics, operating under the aegis of the Royal Society. The members of this Sub-Committee felt that advantage should be taken of the occasion to hold a general conference which might take up the traditions of the successful Optical Conventions held in the years 1905, 1912 and 1926, but in which the series had been interrupted by war and other difficulties. With the encouragement and support of the Royal Society (which made a direct financial grant to the project) an organizing committee was appointed and the London Conference on Optical Instruments, 1950, was the outcome of its activities. It was thought appropriate that the subjects of discussion should be actual instruments and that purely theoretical questions should be largely avoided. A guarantee fund was provided by the optical instrument firms of the Scientific Instrument Manufacturers' Association, and valuable support was also given by the Ministry of Supply and the Admiralty. Scientific Societies, including the Royal Institution, the Royal Astronomical Society, the Royal Microscopical Society, the Royal Photographic Society, and the Society for Visiting Scientists, generously consented to give their support by helping to entertain the members of the Conference by lectures and receptions. The Imperial College of Science and Technology made its large lecture theatre and other accommodation available for meetings, while a large laboratory was used for an exhibition of British Optical Instruments arranged by the British Scientific Instrument Research Association. Support and help was also given by the British Council.

The business sessions of the International Optical Commission were held at Burlington House on 17th and 18th July, and the Proceedings of the London Conference began at Imperial College on 19th July.

The total membership numbered 250, including 28 members of the International Optical Commission. No less than 71 members came from abroad.

The meetings were arranged either as symposia on selected topics or for the presentation of individual papers. In the former, three opening speakers contributed short papers and the meeting was then thrown open for general discussion; in the latter, the individual papers were presented and discussed separately. The Proceedings include both the individual and the symposia papers and also the salient parts of the discussion as selected by the rapporteurs appointed for each session.

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Opening Address

SIR T. MERTON, F.R.S.

THIS is the opening session of the London Conference on Optical Instruments, and to-day we are holding our meeting jointly with the International Optical Commission. It is my pleasant duty to-day to welcome the delegates to the International Optical Commission, and also a number of distinguished visitors from abroad who have come here specially to contribute to our discussion. We have amongst other visitors from the U.S.A., Belgium, Spain, France, Italy, Holland, Sweden, Switzerland, Germany, Finland, and Poland, which I think emphasizes the importance and the international character of the Conference.

I sometimes wonder whether it is generally realised how much we owe to optics for the advancement of science and indeed the advancement of civilization. The discovery of glass was one of the milestones in human progress—where should we be without it? And although optics could not have reached its present state without glass, it is also true that the use of glass in some form or other is a necessity in almost every field of scientific activity. I suppose that the earliest optical work was purely empirical and depended on craftmanship which was handed on from generation to generation. Spectacles were fairly common in the 14th century in Italy, and can be seen in Italian pictures of that period, but optics as we understand it to-day had hardly been born.

It has always seemed to me that progress in any field of science is a periodic phenomenon. You find maxima and minima, and I think that this is true as much of optical science as of any other field. I do not mean to suggest that nothing happens at all during the minima of activity, but they are rather periods of consolidating the gains of the past and tidying up what has been left over from the last maximum. Then someone starts something new and there is an outburst of activity. I think for example that some twenty-five years ago microscopy was in a period of consolidation—perhaps a trifle dull—and without any sign that anything important was in the offing. Now the whole position is changed and I think that we owe the inception of the great activity which obtains in this field of optics in part to the stimulating work of Prof. Zernike, who I had hoped would be with us to-day. Microscopy has come to life, not only with the development of phase contrast, but with the reflection microscope, interference microscopy, and the development of microscopy in the ultra violet. I think that to-day we are in a period of maximum activity in most fields of optics, and there is no sign that we have passed the peak. Looking back over the last quarter of a century, we find an imposing list of advances in addition to those I have mentioned already. The Schmidt reflecting system, synthetic crystals, developments in aspherical surfaces, glasses with new optical properties, the blooming of glass, and a host of other developments, have all contributed to the present period of intense activity.

The days of string and sealingwax and biscuit tins are drawing to their close, and we are becoming more and more dependent in science and in industry on instruments of the highest precision and quality.

Looking back over a much longer period there has been, I think, a profound change in the objectives of research in optics. There was a time when most work in this field was directed towards the elucidation of the fundamental laws of optics, when theory had to be proved step by step by recourse to experiment. To-day the position has changed. There are fewer investigations into the fundamental principles of optics, and almost every advance has been made to meet some very definite and practical need. We depend on our sense of sight for nearly all the quantitative measurements we make. A few observations may still be made by means of our sense of hearing, but apart from a few very mundane applications our other senses have never been used for any serious quantitative measurements. Whilst it is true that we can read an ammeter or gauge the height of a liquid in a U-tube with our unaided vision, the advance of science and technology would have been impossible if we had had to depend on our unaided vision alone. Optics has become an absolutely essential partner in almost every field of natural science, and every new effort is directed to meet what would have been referred to during the war as an operational requirement. Phase contrast may be useful in many fields but the chief beneficiaries are at present undoubtedly the biologists. The Schmidt reflecting system would never have been devised if the astronomers had not required it, and perhaps the most remarkable example is provided by spectroscopy which was born under the name of spectrum analysis but which has only in fact fully earned that title after half a century, during which the principal contributions of the spectroscope to the advance of science lay in the fields of atomic physics and astrophysics.

Optics has become, or is becoming, an applied science. In a field which may be described as pure science, as in pure mathematics, it does not matter whether the objective is clearly defined; the investigator never knows where or how the journey will end, and there is no particular reason why he should do so; but in an applied science it is different. Applied science is not self-fertilizing and it does not flourish in vacuo. It is therefore of the utmost importance to maintain the closest possible liason with every field of scientific activity and further to ensure that researchers in optics should meet one another to exchange views and to hear what is going on in every part of the world. It is for this reason that the London Conference on Optical Instruments is of special importance. Optical instruments cover a very wide range but the Organizing Committee have thought it best to choose a limited but practical field for the subjects under discussion, and it is hoped that speakers will bear this aim in mind, more especially at those meetings at which definite instruments are dealt with.

The Organizing Committee have also arranged visits to a number of establishments and laboratories; but I think that perhaps the most important thing about this Conference is that it gives us a chance of meeting one another and hearing what is going on in every part of the world.

I should like to express the thanks of this Conference to the Rector and Governors of the Imperial College, and also to Sir George Thomson for allowing us the use of the rooms of the College.

PHOTOGRAPHIC AND PROJECTION LENSES

1. Some Recent Developments in Photographic Objectives

R. KINGSLAKE
(Eastman Kodak Co., U.S.A.)

THE growth of the Photographic Objective has been well documented[1] up to 1940. Since then, in spite of and perhaps because of the war, the last decade has seen a considerable advance in photographic objective design in many countries, as evidenced by the issue of over 170 photographic lens patents * since January 1940. Many of these are extensions of known types, but there has been a sufficient number of new developments to justify a survey of the situation as it exists today.

High-index Glasses

Probably the greatest single reason for much of the recent activity in photographic lens design is the introduction of high-index glasses by G. W. Morey and the Eastman Kodak Company[2] [3]. The chart in Fig. 1.1 shows all the glasses in Chance's 1940 catalogue, representing the available range of optical glasses in pre-war days. On the same chart have been added the new glasses, not available in 1940, taken from Chance's 1948 list (" C " on chart), Schott's 1949 list (marked " S "), and the Eastman Kodak post-war list[3] (marked " K "). These high-index types have been the lens designer's dream for at least 70 years, and it is scarcely surprising to find that attempts have been made to incorporate them in almost all the standard types of photographic objective. At least 56 patents issued since 1940 refer specifically to these new types of glass in claims or examples. Many lenses are now in current production embodying one or more elements made of these glasses.

A brief review of the use of high-index glass as a " crown " in the positive components of lenses of various types has been given by G. H. Aklin.[4] Briefly, the higher index permits the use of flatter curves which in its turn aids zonal spherical aberration and field zones of astigmatism. In lenses of the Tessar type, the effect of using high-index glass in one or both of the positive elements is to make the tangential and sagittal fields come together, and thus reduce the astigmatic difference very considerably. This effect is seen in the examples cited in some recent patents.[5] [7] Indeed, it is fair to say that the new 1·70/55 glass is as great an improvement over the pre-war dense barium crown 1·61/57, as that glass was over common crown, 1·52/58.

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*Duplicates in other countries are not regarded as separate patents.

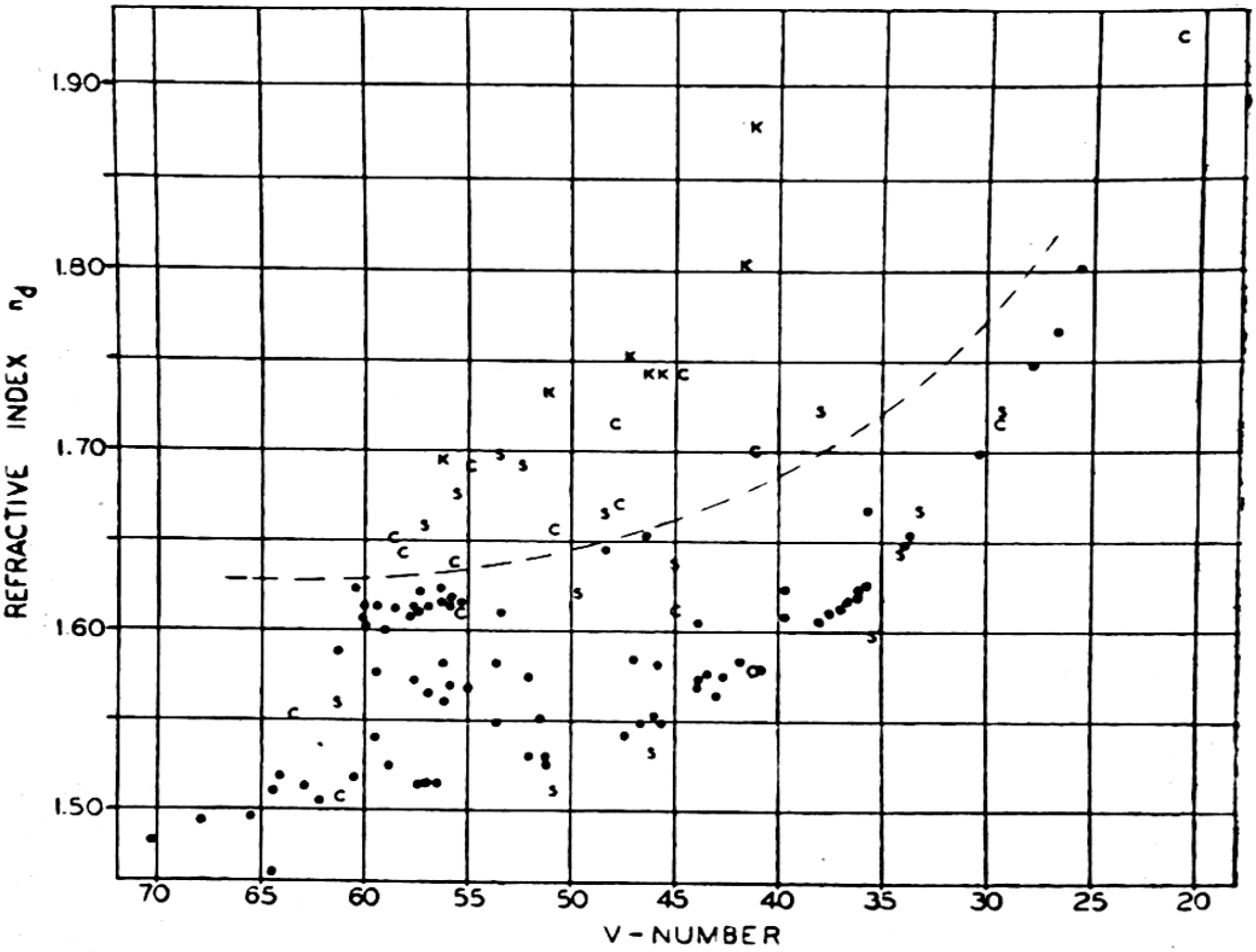

Fig. 1.1. Chart showing range of pre-war optical glasses wth new glasses introduced since 1940. " C "=Chance's 1948 list ; " S "=Schott's 1949 list ; " K "=Eastman Kodak post-war list.

Double Lenses

A few nearly symmetrical double lenses (" duplets ") have been recently designed, including some long-focused Ross Xpres [8] aerial and process lenses, and a wide-angle cemented lens [9] containing high-index glasses.

The Triplet and its Modifications

Although the Cooke Triplet lens is the simplest of all photographic objectives, and although over 40 patents have been granted for slight modifications of it since the original Dennis Taylor design of 1893, it has not yet reached finality and no less than 14 patents for lenses of this type have been granted since 1940. Seven of these contain specific reference to high-index glasses. Incidentally, by using these glasses, it has been found possible[10] to develop a satisfactory triplet of aperture as high as f/1·9, covering a half-field of 13°, for 8-mm. ciné cameras.

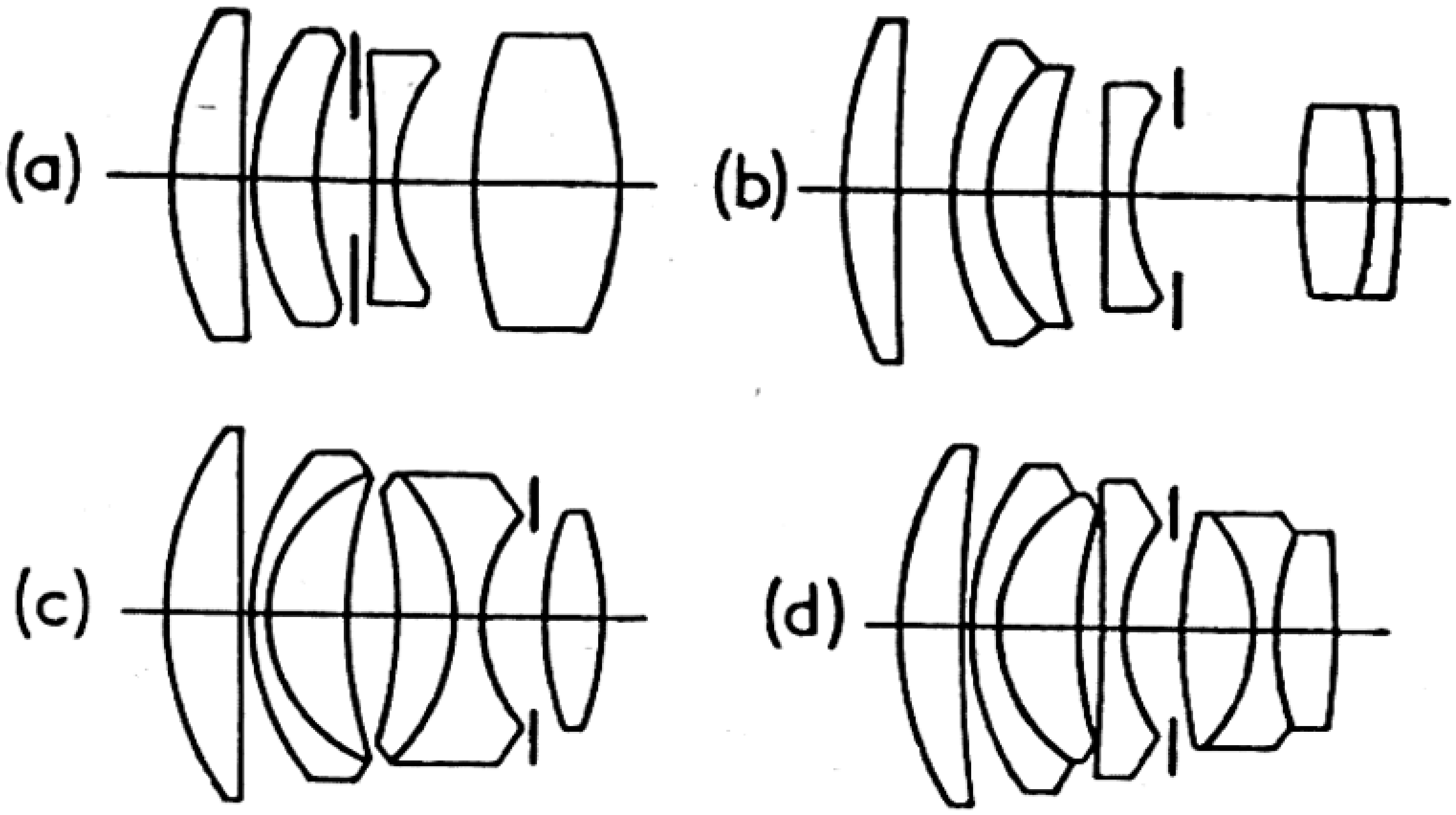

FIG. 1.2. Modern lenses of the plus-plus minus-minus type.
(a) Kodak Ciné Ektar 25-mm. f/1.4 ; (b) Kodak Ciné Ektar 63-mm. f/2.0 ; (c) Kern Switar and Pizar 25-mm. f/1.4 ; (d) Kodak Fluro-Ektar 52-mm. and 111-mm. f/1.5.

The most remarkable modification of the original triplet is that in which an additional meniscus-shaped component has been inserted into the front airspace. This type, due principally to L. Bertele, has been actively exploited in the past decade, and no less than 30 patents have been granted covering it. Some familiar examples are the Kodak Fluro-Ektar f/1·5 lenses[11] of focal length 52 and 111 mm. (Fig. 1.2d) ; the Kern Switar and Pizar ciné lenses of 25-mm. focus and f/1·4 aperture (Fig. 1.2c) ; and many varieties of the Sonnar developed by Zeiss[1K] during the war for special purposes. The Kodak 25-mm. f/1·9 Ciné Ektar[12] uses only four elements (Fig. 1.2a), and it is thus similar in construction to the Bell & Howell Lumax lens which appeared just before the war. Another new lens of this type is the Bausch & Lomb f/3·5 Tele Animar[13] of 75- and 100-mm. focal length. A more complicated example is the Kodak 63-mm. f/2 Ciné Ektar lens[14] [15] (Fig. 1.2b), covering a half-field of about 8°.

Some other modifications of the Triplet have been used very successfully; for example, there has been an extensive development of the Pentac or Heliar type by F. E. Altman.[16] In this lens both the front and rear components contain a collective cemented surface, by means of which the high-order coma and oblique spherical aberration can be readily controlled in a simple manner. Typical recent lenses of this type are the Kodak 63-mm. f/8 Microfile Ektar and the 100-mm. f/3·5 Ektar supplied on the Medalist camera. Some 12 patents have been issued since 1940 embodying this and other variations of the Triplet lens.

Four-element Systems

A few four-element systems have been recently developed, a notable example being the new Wray f/4·5 Lustrar.[17] There has been some interest also in the type in which the negative elements are convex towards the diaphragm.[13]

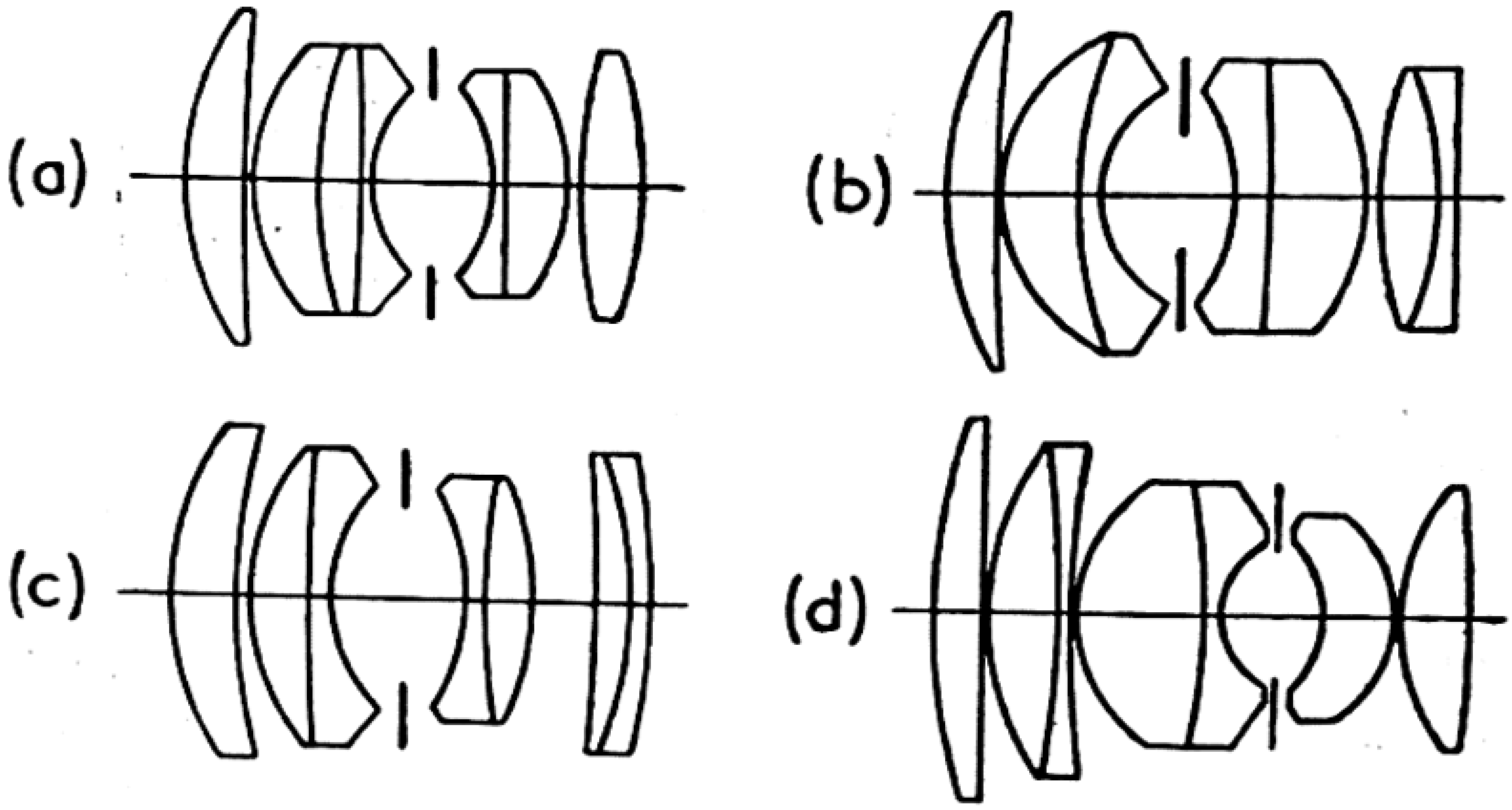

FIG. 1.3. Some new meniscus type lenses.
(a) Dallmeyer "Septac" anastigmat 52-mm. f/1.5; (b) Kodak Ciné Ektar 25-mm. f/1.4; (c) Kodak Aero Ektars 7" and 12" f/2.5; (d) Wray C.R.T. lenses f/1.0.

High-aperture Meniscus Lenses

Much of the design activity of recent years has been directed towards the securing of higher apertures with improved definition. Thus, about 40 patents have been issued since 1940 describing lenses of the well-known Planar or Opic type using meniscus components with compound flints. High aperture lenses of this kind have been made for many years for miniature cameras, including the Summar, Summitar, and Xenon, and also for many 35-mm. motion picture cameras such as the Speed Panchro and the

Baltar series. Some of the more interesting recent developments in this type are the 50-mm. Summarit f/1·5 and the 85-mm. Summarex f/1·5 for the Leica camera ; the Taylor-Hobson Amotal[18] f/2 for the Foton camera, and Ivotal f/1·4 for 16-mm. ciné ; the 52-mm. Dallmeyer " Septac " Anastigmat[19] f/1·5 (Fig. 1.3a) ; the Kodak 7-inch and 12-inch f/2·5 Aero Ektars[20] (Fig. 1.3c) ; the Kodak 25-mm. f/1·4 Ciné Ektar[14] (Fig. 1.3b) ; the Ross Xtralux[21] f/2 ; and the Bausch and Lomb Super Cinephor[22] f/1·6 projection lens. Almost the only fault to be found in this type of construction is the overcorrected oblique spherical aberration which arises at the two strong concave surfaces close to the diaphragm.

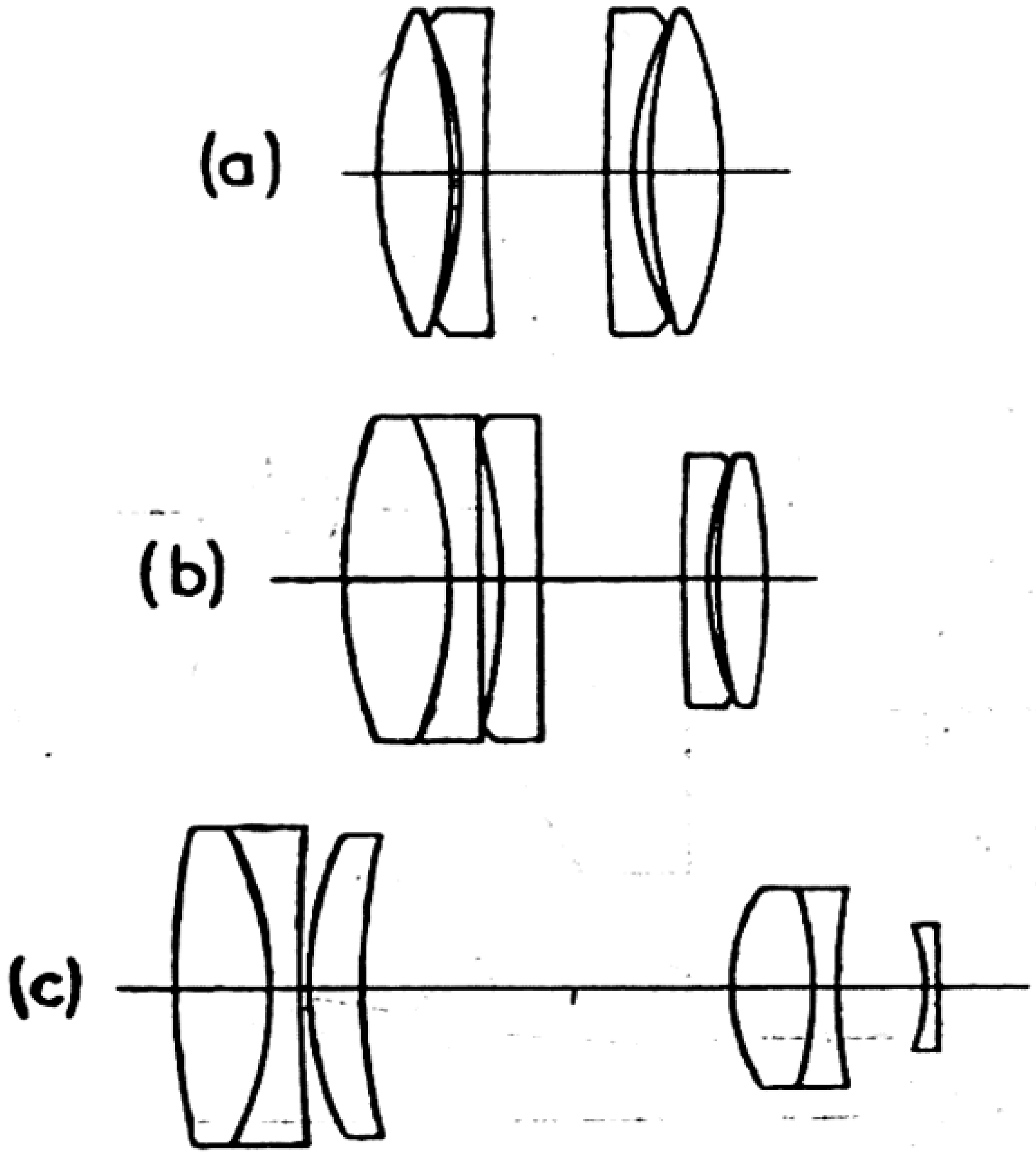

FIG. 1.4. Recent Petzval lens modifications.
(a) Use of narrow air-space ; (b) negative element behind front component to correct S.A. ; (c) addition of Smyth lens to act as a field flattener.

An interesting recent variation of the Planar type has been made by C. G. Wynne, by eliminating the cemented surface in the rear negative component. Using this principle, he has designed the Wray f/2 Unilite[23a] for miniature cameras, the f/1·9 Ciné Unilite,[23b] and the f/1 C.R.T. lens[24] (Fig. 1.3d).

Petzval-type Lenses

Whenever a high-aperture lens is required to cover a narrow angular field, as for example in the lenses of long focal length for motion-picture cameras and projectors, the Petzval type is usually employed because of its excellent axial image correction. In its original form, this lens comprised two thin achromats widely spaced, using low-index crowns with normal flints, but the Petzval sum was large. By the use of narrow airspaces within the cemented components (Fig. 1.4a), crown glasses of higher index could be employed,[25] with a corresponding improvement in the Petzval sum. Recently several Petzval-type lenses[26] [27] have been designed in which the crown index is actually higher than the flint index, and in some designs the spherical aberration has been corrected by incorporating a weak meniscus-shaped negative element (Fig. 1.4b) close behind the front component[28] [29] With the further addition of a Smyth-lens to act as a field flattener,[30] a 2-inch projection lens has been constructed of f/1·5 aperture, covering a 7° half-field, giving 90-line resolution and high image contrast over the entire 16-mm. field (Fig. 1.4c).

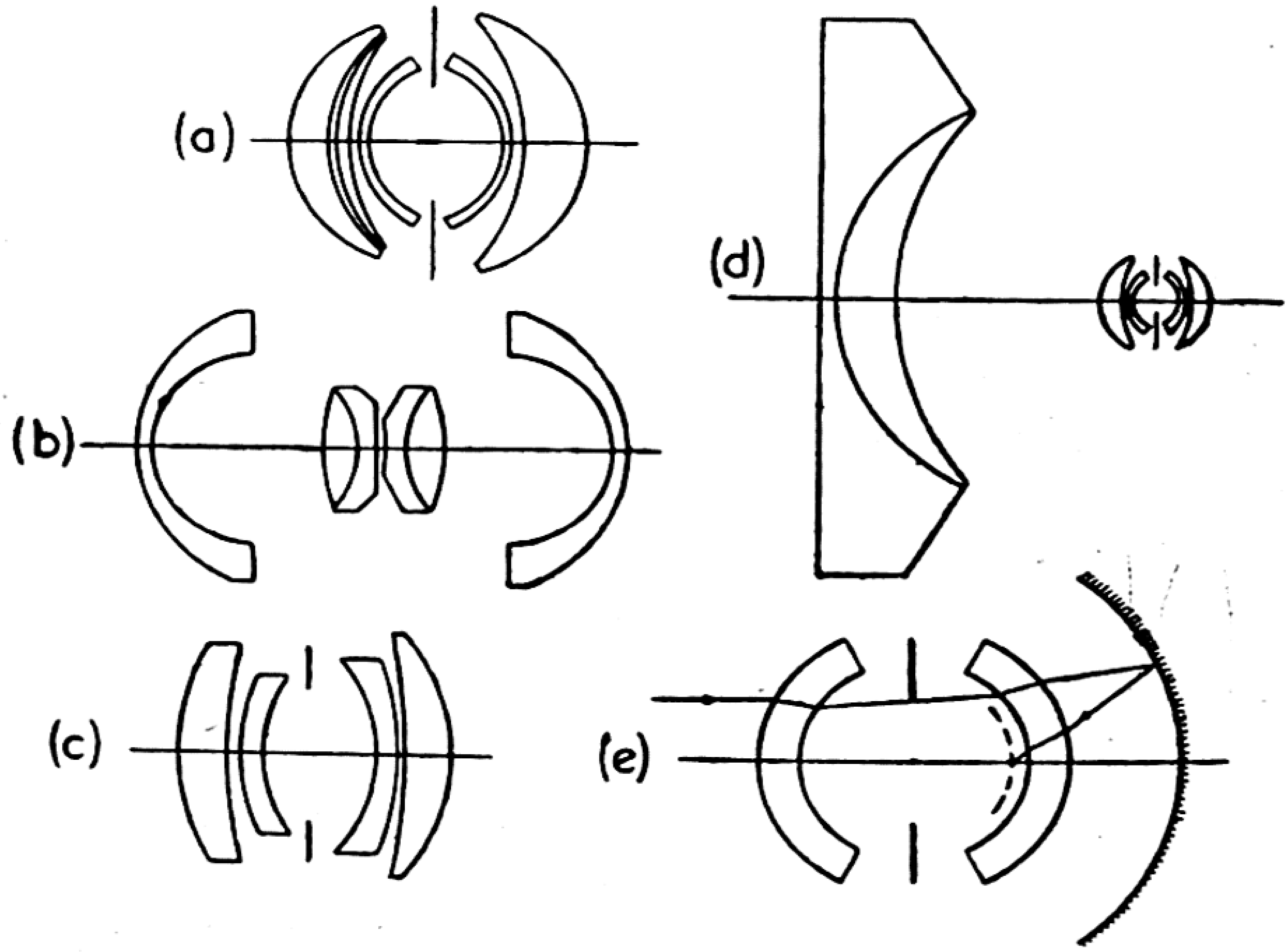

Fig. 1.5. Types of wide angle lenses.
(a) Topogon with split front element; (b) Roussinov's modification of the Topogon; (c) wide field Ektar lens; (d) Zeiss " Pleon " and " Sphaerogon " lenses; (e) the Bouwers-Maksutov system.

Wide-angle Lenses

Wide-angle lenses have not been neglected during the period under discussion. W. B. Rayton attempted to improve the residual distortion in the Topogon[31] by splitting the front element into two (Fig. 1.5a); and Kodak announced a series of so-called Wide

Field Ektar lenses for commercial photography, covering a half field of 37° at f/6·3 (Fig. 1.5c). Messrs. Wray Ltd. have recently developed an f/6·3 Wide Angle Lustrar of similar construction covering a 90° field at f/11. The Russian designer M. Roussinov has designed a novel variation [32] of the Topogon in which the positive power is concentrated near the diaphragm, between two thin shell-like negative hemispheres (Fig. 1.5b).

One of the most interesting developments in wide-angle lenses is the Zeiss extension of the Hill "Sky-lens" principle in the Pleon [33] and Sphaerogon [34] lenses patented just before the war. In these lenses, a large flat concave component is used as a collector to form a strongly distorted virtual image of a wide angular range of objects, which in turn is photographed with a normal-type lens situated behind it (Fig. 1.5d). The distorted negative image can then be rectified by projection through a similar distorting system to make undistorted prints. A very real advantage of this system is that the distortion largely neutralizes the serious $\cos^4$ and vignetting properties of a normal wide-angle lens,[35] so that the illumination can be made practically uniform over the whole field.

Telephoto Systems

After a period of inactivity since the 1920's, the Telephoto lens has suddenly come back into a spell of great popularity. No less than 23 telephoto lens patents have appeared since 1940, and the various Air Corps of the world are busily engaged in developing larger and better aerial lenses [36] [37] of this type. A typical German design is the Telikon,[38] covering a half field of 15° at f/6·3. High-index glasses are not used very extensively in telephoto lenses, and then more often as flints than as crowns since the Petzval sum of a telephoto lens has often too small a positive, or even a negative, value. In small sizes, telephoto lenses with apertures as high as f/2·0 to f/2·5 have been described,[39] [41] but the trend is to use ordinary lenses wherever possible, especially in focal lengths under about 8 or 10 inches, for then the particular advantage of a short total length from front vertex to film plane is not of much significance.

Reversed Telephoto Lenses

Mounting a negative component at a considerable distance in front of the anterior focal point of a positive component has several important consequences: it shortens the focal length, it widens the angular field, and it increases the back-focus clearance. At times all of these properties are of value, and six patents [42] covering systems of this type have appeared since 1940.

Reversed telephoto systems are exceptionally useful as wide angle lenses on 8-mm. and 16-mm. cameras, the Elgeet Company in U.S.A. having recently announced a 7-mm. f/2·5, and a 13-mm. f/1·5 reversed telephoto lens for this purpose.

Afocal Attachment Lenses

The use of afocal Galilean telescopes as attachment lenses to change the focal length of a lens without altering its back focus is becoming increasingly popular, especially as wide-angle attachments. A number of these have appeared recently in America, sold at a low price but unfortunately of rather low optical quality. However, with careful design, these systems can be very satisfactory and give the equivalent of a wide-angle lens having a high relative aperture and exceptionally long back focus. The diaphragm markings of a lens are unaffected by the use of this form of attachment. The long-focus, or telephoto, attachments are used less frequently, because a normal long-focus lens is easier to make than a short-focus lens plus an attachment, and because the front component of the attachment must be very large to avoid excessive vignetting.

Zoom Lenses

A new zoom lens known as the Zoomar [43] has recently appeared on the American market, which represents a complete departure from previous attempts to make a vari-focal lens. The system comprises five members (Fig. 1.6) : (*a*) a front interchangeable system to form a real image, which may be focused to any object distance ; (*b*) a sliding system to vary the size of this real image ; (*c*) a fixed relay system to form a second (erect) image ; (*d*) a sliding field-lens close to the erect image, the power and position of which are chosen so that if lens (*d*) and lens (*b*) are moved through exactly the same distance, the second image will remain substantially stationary ; and lastly (*e*) a second fixed relay system containing the iris diaphragm, to form the final inverted image on the film in the camera. Since the two sliding components move through equal distances, they may be directly coupled together, and no cams or other devices are needed. Furthermore, the relative aperture of the system remains constant during a zoom since all the moving parts lie ahead of the diaphragm. The Zoomar lens is made in two sizes, an f/2·8 for 16-mm. film and an f/4·5 for 35-mm. film.

Another simpler zoom device has recently been announced, namely, the Pan-Cinor[44] of S.O.M.—Berthiot (Fig. 1.6). This is an afocal zoom attachment which is mounted in front of an ordinary lens, and it contains two coupled sliding positive elements each being followed by a fixed negative element. By a suitable choice of powers and separations, it is possible in this way to vary the focal length of the system over a range of over 3 : 1 without noticeably affecting the location of the focal plane. The diaphragm is, of course, in the main lens and remains fixed during a zoom.

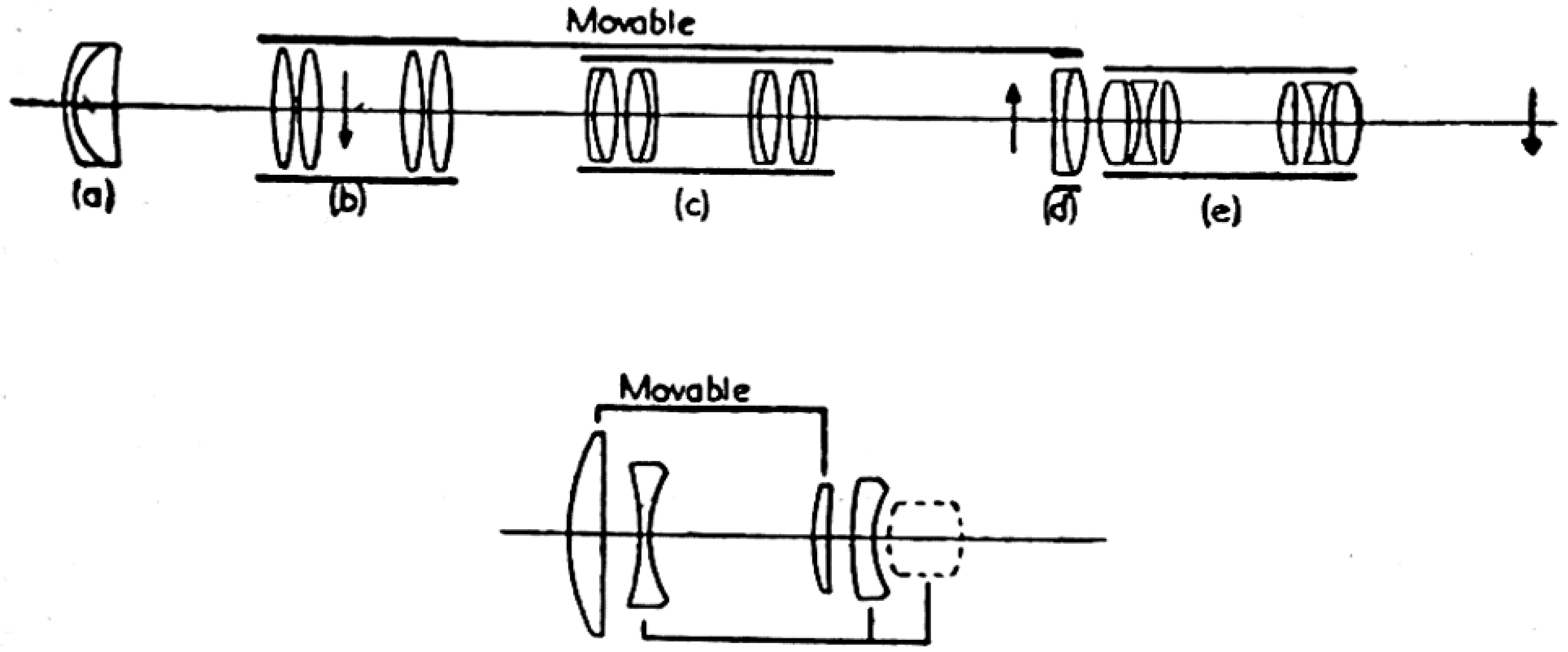

Fig. 1.6. Recent types of Zoom lenses: (top) the Zoomar; (below) the Pan-Cinor.

Catadioptric Systems

During the past ten years there has been a very great advance in the development of reflective optical systems for use as photographic objectives. The inspiration for this activity was the invention of the Schmidt camera by Bernhard Schmidt[45][46] of Bergedorf, in 1931. There is no novelty in a mirror-lens combination, in which an aspheric lens surface is merely used to compensate the spherical aberration of the mirror[47]. Schmidt's invention, however, lay in the placing of a stop and correcting element at the centre of curvature of a spherical mirror, to eliminate coma and astigmatism automatically over a concentric focal surface of finite extent. Once this possibility had become realized, it was a straightforward matter to replace the difficult aspheric plate by a zero-power system of spherical surfaces,[48][51] and later, by monocentric refracting corrector systems in which the oblique images are completely identical with the central image. This latter device (Fig. 1.5e) was pioneered independently by A. Bouwers[52] in Holland and D. D. Maksutov[53] in Russia, with a slight priority in favour of Bouwers. A combination of the monocentric lens corrector with an aspheric plate has been independently proposed by Baker,[54] Bouwers,[55] Hawkins and Linfoot,[56] and Wynne.[57] It is claimed that greatly improved definition can be obtained by this combination, chiefly because the sphero-chromatism of the aspheric plate and of the concentric corrector are of opposite sign.

The principal photographic applications of reflective systems have been in astronomy, and also more recently, in X-ray fluorography where the very highest aperture ratios are required. Two Schmidt cameras[58] for this purpose have been manufactured by C. H. Helm in Denmark, one of 4-inch focus and f/0·75 effective aperture for 35-mm. film, and the other 6-inch focus and f/0·85 effective aperture for 70-mm. film. It is necessary to compress the film into a convex spherical form during exposure so that it will fit the spherical field of the system. An alternative system has been suggested by R. E. Hopkins[59] of the University of Rochester, who has designed and built an f/1 lens with a strongly curved field, the film being curved into the necessary concavity by means of gas or air pressure between the back of the lens and the film. Some other monocentric lenses for X-ray fluorography have been described by Greenstein and Henyey of Yerkes Observatory,[60] in which an achromatised correcting lens of the Bouwers-Maksutov type has been employed.

Some very large catadioptric systems were used during the war by the Germans with an electronic image-tube for infrared vision. One example was of 640-mm. focus and f/1·4 aperture, somewhat resembling the Gabor system[48] in form.

Lenses with Increased Depth of Field

The depth of field of a perfect lens is, of course, fixed by the laws of geometrical optics and by diffraction effects. To increase the depth something must be sacrificed, and most devices for increasing depth utilise the principle that a sharp image will be recorded photographically more readily than a blurred image. Large amounts of spherical and chromatic aberration have been employed for this purpose, and a lens attachment with a conicoid surface has been used. One recent worker in this field is L. M.

Dieterich, who caused a negative element within a lens to vibrate longitudinally [61] [62] by means of an electrical loud-speaker mechanism. Near objects are in focus at one end of the range and far objects at the other, thus during the exposure every object will come into focus at one point in the vibration cycle. Dieterich points out that care must be taken in the design of any moving-lens device of this kind to ensure that the size of the image does not change while the lens is being moved. Another proposal is that of S. E. Garutso,[63] who adds one or more annular lens elements to an existing well-corrected lens. Light from near objects passing through the annulus comes to the same focal plane as light from distant objects through the hole in the middle, thus objects at all distances will be imaged fairly sharply with such a lens.

Other Optical Materials

In spite of the wide range of transparent plastic materials now available, very little use has been made of plastic optical components. One reason is that plasticity is just what is not wanted in lenses. To remove all signs of striae and inhomogeneity in a plastic lens is harder than in glass, and it generally requires the plastic monomer to be polymerised in the lens mould. Even then, shrinkage and moisture absorption cause a significant change in the properties of the lens with time, and the high temperature coefficients of refractive index and of thermal expansion cause a plastic lens to vary widely in focal length with temperature. D. S. Grey has suggested [64] that a composite lens should be made in which all the power is concentrated in a single glass element, the powers of the positive and negative plastic correcting components being chosen to yield a system which is " athermal " in addition to the other optical corrections. Unfortunately, too, there are no plastics which are equivalent to barium crown glasses with a high index and a low dispersive power. On the whole, there appears to be very little in favour of plastic lenses and much to be said against them.

Synthetic optical crystals are now becoming available, the most interesting being calcium fluoride and the alkali halides such as potassium bromide and iodide. For special purposes, these materials can be used to eliminate secondary spectrum, but they are extremely undesirable in the shop on account of their softness, brittleness, and solubility in water. They are also afflicted with high temperature coefficients.

The Philips Company has been successful in moulding gelatin on glass in such a way that when dried it will have the desired thickness to constitute a Schmidt plate for a home television projector.[65]

Mechanical Developments

Fashions in lens mounts change little with time. However, there is now a trend towards departing from a black exterior finish and using either anodized aluminium or chrome-plated brass. Iris diaphragms are now frequently made with specially shaped leaves to give a more uniform scale, and in the new Kodak Process Ektars the iris scale is completely uniform so that the angular rotation of the ring required to reduce the aperture by $\sqrt{2}$, from one stop marking to the next, is the same in all parts of the scale from f/10 down to f/256. This feature enables a simple slide rule to be added to the iris ring so that any desired aperture ratio in the image space can be set at once for any image magnification.

The use of anti-reflection surface coatings is now practically universal in all but the very cheapest lenses. Some manufacturers are using photometrically calibrated aperture markings (T-stops)[66] in an effort to take into account the variations in transmittance between coated and uncoated lenses, but it must be admitted that this move is almost too late to be of much value.

Plastic lens cements are often used in place of Canada balsam, as they withstand high and low temperatures much better than balsam. They are, however, more troublesome in the factory, and cements of the thermosetting type are almost impossible to remove if it should be necessary to uncement a lens.

Aspheric Surfaces

A few attempts have been made to incorporate aspheric surfaces in photographic lenses, but the very great difficulties involved in manufacturing non-spherical surfaces with the necessary precision have discouraged designers from using them. It is still too early to say definitely whether the use of aspheric surfaces will effect any revolutionary improvements in lenses that could not be accomplished in some other way.

References in this Paper are given on page 14.

SOMMAIRE | SUMMARY

Pendant la dernière décade de nombreux progrès ont été effectués en Europe et en Amérique dans le domaine des objectifs photographiques ou de projéction. Les ouvertures et les angles de champ ont été augmentés mais l'effort a porté principalement sur la qualité de l'image et sur la simplification de la construction, grace à l'utilisation de nouveaux verres d'indice élévé. Les matieres plastiques et les surfaces asphériques ont été utilisés mais jusqu'ici avec peu de succès.

Un progrès remarquable a été effectué dans l'utilisation des miroirs; des systèmes catadioptriques ont été fabriqués dans des buts assez variés; objectifs pour la photographie aérienne, photothéodolites, photographie des écrans fluorescents pour rayons X, et microphotographie.

Plusiers nouveaux téleobjectifs et objectifs à grand champ ont été étudiés pour la photographie aérienne à haute altitude et la solution utilisée dans le " sky-lens " a été appliquée également.

Un nouvel objectif à distance focale variable ("zoom lens") a été récemment utilisé pour la prise de vues des actualitiés cinématographiques et les caméras de télévision. Plusiers firmes fabriquent des accessoires permetteant d'augmenter ou de diminuer la distance focale des objectifs photographiques ordinaires. On a également tenté d'augmenter la profondeur de champ des objectifs sans perdre de luminosité; plusiers solutions ont été proposées.

La construction des objectifs a également été étudiée; c'est ainsi que l'on a réalisé de nouveaux diaphragmes iris à échelle linèare; que l'on a utilisé de nouvelles matieres plastiques pour le collage des lentilles. Enfin l'emploi des films anti-refléchissants et des étalonages photométriques des ouvertures numériques s'est généralisé.

During the past decade there have been many advances in photographic and projection objectives, both in Europe and in America. Apertures and fields have been increased somewhat, but emphasis has been placed mainly on improved image quality, and on simplified construction using new high-index optical glasses. Plastic lenses and aspherical surfaces have been used, but with little success so far.

There has been an outstanding advance in the use of reflecting surfaces in photographic objectives, and so-called Catadioptric systems have been made for a variety of purposes, such as aerial lenses, phototheodolites, X-ray fluoroscope cameras, and for photomicrography.

PHOTOGRAPHIC AND PROJECTION LENSES

Several new aerial telephoto and wide-angle lenses have been developed to meet the needs of high-flying aircraft, and the well-known "Sky-lens" principle has been successfully applied to aerial photography.

A new Zoom lens has recently come into regular use on news-reel and television cameras. Several firms are manufacturing telephoto and wide-angle afocal attachments to change the equivalent focal length of ordinary cameras. The desire for some way to increase the depth of field of lenses without loss of lens speed is still with us, and several proposals for doing this have been advanced.

Lens manufacture has received its due share of attention, with new iris diaphragms having a uniform scale, plastic lens cements, the extensive use of anti-reflection coatings, and photometric aperture calibration.

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2. A Class of Symmetrical Systems of Variable Power

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THE literature relating to systems of variable power, so-called zoom or vari-focal lenses, consists mainly of patent specifications and brief technical notes. Patent specifications do not generally disclose more than the manner in which the inventions achieve their claimed performance : neither critical accounts of the underlying theory are to be found in them, nor are any references given to other inventions, except in a very general way. Not only is this the position that obtains in the patent literature of variable power systems, but such also seems to be the state of the scanty technical literature. Because of this a summary of the known earlier systems is first given.

Objectives of variable focal length seem first to have been needed as ciné-projection lenses. The purpose of vari-focal projection lenses was to permit the use of the same lens with different distances between the projector and the screen. In such an objective, the focus could be adjusted after the correct image size had been obtained. For this reason the conditions to be fulfilled by a vari-focal projection lens are less stringent than those which must be satisfied by a lens of variable power which is intended for use with a ciné-camera. For the purpose of using such a lens is then to give the impression (when the film is projected) of the camera approaching, or receding from, objects in the field of view. The camera itself remains stationary during the filming of the " zoom " shot. The scene is thus filmed continuously while the image size is varied, and the image must therefore remain continuously in focus on the film.

Variable power systems of this type have taken two principal forms. In the first, the afocal camera attachments, a telescopic system is placed in front of an ordinary fixed focus objective. If M=magnification of the afocal attachment, and F=equivalent focal length of the camera lens, the equivalent focal length of the combined system is equal to MF. By causing M to vary, the effective focal length is made to vary. The second type of system comprises objectives of finite focal length, constructed similarly to systems of fixed focal length, but in which the equivalent focal length is made to vary by suitably displacing two or more components of the system.

The advantages of an afocal variable power attachment are twofold. In the first place, any fixed-focus objective can be converted to a zoom lens, so that one variable power unit provides in effect a whole range of such lenses. More important than this is the automatic control of the aperture ratio. If d is the diameter of the entrance pupil of the fixed-focus lens, of focal length F, the aperture ratio is F/d. If now a telescope of magnification M is placed in front of the fixed-focus lens, both F and d are increased in the same ratio, M. Hence the aperture ratio is kept constant by the simple expedient of keeping a constant stop-value on the fixed-focus lens.

A disadvantage of the afocal zoom attachment derives from the possibility of using it with lenses of widely differing focal lengths. For the short-focus lenses will require the attachment to cover a large angle of field, whereas the long focus lenses will require it to have an exit-pupil of large diameter. Because of this it is desirable to incorporate an afocal system in a zoom lens of finite focal length, and having a high zoom ratio. For then one fixed-focus lens is used, whose focal length is the geometric mean of the extreme focal lengths. If the zoom ratio is large enough the desired range of focal lengths may still be obtained. What is more, the fixed-focus component no longer needs to be of complex construction, since its astigmatism and field curvature can be corrected by the residual aberrations of the afocal part of the system. In practice a simple achromatic doublet lens has been found quite satisfactory.

Earlier Systems of Variable Power

The systems described below may not include all the known systems of variable power. They are those which have come to light as a result of a search of the literature and particulars of patent specifications.

(1) Allen (U.S. Patent 696,788, 1902) described a number of varifocal projection lenses in which a movable middle component can be displaced axially between two outer fixed components. In the preferred form a single negative lens, of focal length $-F/2$, moves between two outer fixed positive components. The front component has a focal length $+F$, and the rear (compound) component has a focal length $+F/4$. The image does not remain exactly in focus on varying its size, and for this reason a small relative aperture must be used. In this respect the invention seems to have anticipated that of Gramatski (*vide infra*), who constructed an afocal attachment of this kind.

In this system, as in the later one of Gramatski, the moving lens has a magnification equal to -1 when in its mean position. The reason for this is easily seen. Thus, if T = distance between object and image, and the lens is assumed to have nodes separated by a distance δ, then

$$T=\delta+l'-l \tag{1}$$

must remain constant if the image is to remain fixed in space. l, l' are the distances of the object and image from the appropriate nodes. If M=magnification, and F = focal length of the lens,

$$l=\left(\frac{1}{M}-1\right)F\ ,\ l'=(1-M)F \tag{2}$$

and, from (1),

$$T=\delta+\left(2-M-\frac{1}{M}\right)F$$

For T to have a stationary value as the lens is displaced

$$\frac{dT}{dM}=\left(-1+\frac{1}{M^2}\right)F=O$$

This is satisfied when $M=\pm 1$, that is in the cases of a field lens and of a lens working at unit (negative) magnification. It is the latter case which seems to have been employed by both Allen and Gramatski. On the other hand both cases occur in the Zoomar lens of F. G. Back (*vide infra*).

(2) Naumann (U.S. Patent 1,988,390, 1935: Germany, 1931) described a system consisting of three cemented doublets, of which the front two move differentially. The objective is of finite focal length and can be used as either a camera or projection lens.

(3) Warmisham and Mitchell (*J.S.M.P.E.*, **19**, **4**, p. 329, Oct. 1932: U.S. Patent 1,947,669, 1934) described a lens of considerable optical and mechanical complexity. The lenses are arranged in three groups, the latter two of which are moved by an arrange-

ment of cams. A further set of cams is disposed in a selector box for controlling the iris diaphragm. In this, as in the case of Naumann, it is difficult to see from the published accounts what optical principles are employed for ensuring good correction of the aberrations.

(4) S.M.M.H. Corporation (Brit. Patent 467,487, 1937 : U.S. 1934) claimed a system consisting of a moving positive component spaced between two negative components, the front one of which moves differentially with the middle positive component. The two moving components have equal equivalent focal lengths, but of opposite sign. By this means a simple mechanical linkage suffices to obtain the non-linear movements of the components without having recourse to cams. The theory is a simple consequence of Newton's lens formula.

(5) Gramatski (Brit. Patent 449,434, Nov. 1935 : Germany 1935), referred to the earlier use of Galilean telescopes placed in front of a fixed-focus camera lens for the purpose of increasing (or decreasing) the effective focal length. His systems are then shown to derive from magnifying and reversed Galilean telescopes by splitting, in the one case, the front positive lens into a negative and a positive lens. Alternatively the negative lens may be split into a positive and a negative lens. Two types of afocal variable magnification system are thus obtained. In the one a positive lens may be moved between two fixed outer negative lenses of equal focal length : in the other a negative lens may be moved between two fixed outer positive lenses of equal focal length. In each case the middle lens has a magnification —1 when in its mean position : and, in its extreme positions, this magnification has the values $-m$ and $-1/m$, where $m^2 =$ ratio of maximum to minimum magnification. Since the two outer lenses have equal focal lengths, the magnification of the afocal system is the same as that of the middle lens. It is not difficult to see that the image will be formed in its correct position in space for at most two magnifications. The defect of focus will follow a parabolic law as the magnification varies. A restricted aperture is necessary in order to tolerate this defect of focus. Nevertheless, a system having a (so-called) zoom ratio 2 : 1 has appeared having a pupil of some 12 mm. diameter. This is possible because all the lenses of the focal system are of long focal length. For, in consequence of the resulting low relative apertures, the aberrations of the separate components are small even using three single elements.

The negative-positive-negative system (Fig. 2.1) seems to have been preferred by Gramatski. For this is the preferred form given in his patent specification, and it was lenses of this construction which were manufactured in Germany. It will be seen later that there are strong reasons for preferring the positive-negative-positive construction. The relative apertures of the separate components are very much less in this case, and much better correction of aberration is possible. A possible exception to this is provided by a system required to cover a large angle of field, for here a front negative lens greatly reduces the convergence of oblique pencils. It seems to have been this consideration that led Gramatski to adopt the n-p-n form, since he claims that " to reduce distortion the outer lenses are given the form of meniscus lenses ".

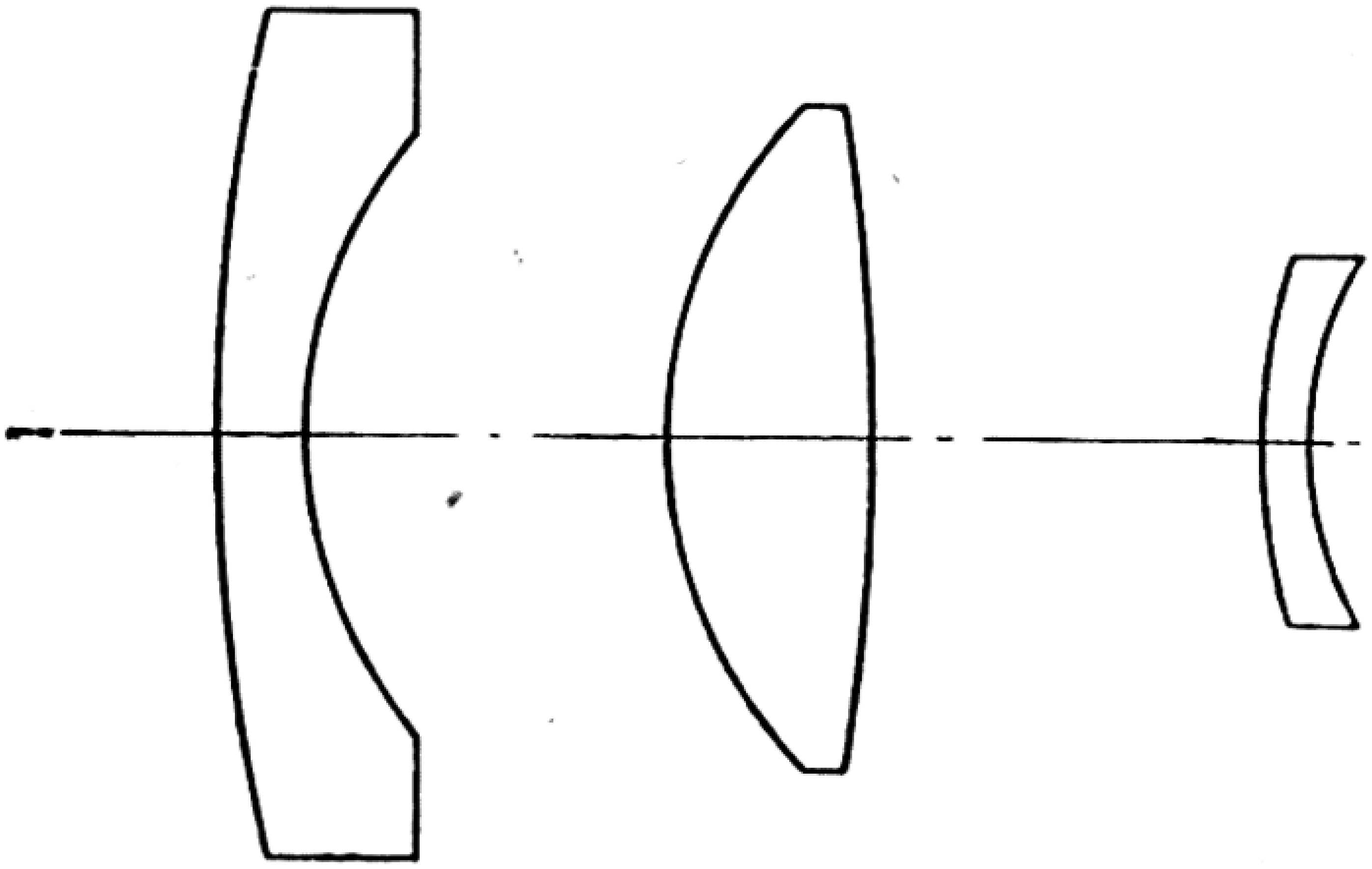

FIG. 2.1. Gramatski's negative-positive-negative variable power system.

The Gramatski systems possess symmetry as regards the distribution of powers of the lenses and the movement of the middle lens. There is, however, no suggestion of symmetry in the shapes of the lenses. These systems are therefore only semi-symmetrical.

(6) Capstaff *et alia* (U.S. Patent 2,165,341, 1939) claimed afocal systems of the same construction as those of Gramatski, but having symmetry also in the shapes of the lens elements. The middle component is moved by means of a lead screw, which also operates a helical cam-slot for imparting small movements to the front component in order to maintain an accurate focus. No explicit claim seems to have been made of the advantages of a completely symmetrical system in the maintenance of the correction of the aberrations during operation of the system. Indeed it seems doubtful whether sufficient degrees of freedom exist with this type of system. For the lens powers and dispersions are fixed in order

to give the required range of magnification and for the correction of the chromatic aberration respectively. There remain only the shape of the outer lenses and the refractive indices of the glass types used. It will be seen later that both spherical aberration and coma need to be corrected for either of the two extreme magnifications, and it does not seem to be likely that this can be achieved with such limited degrees of freedom.

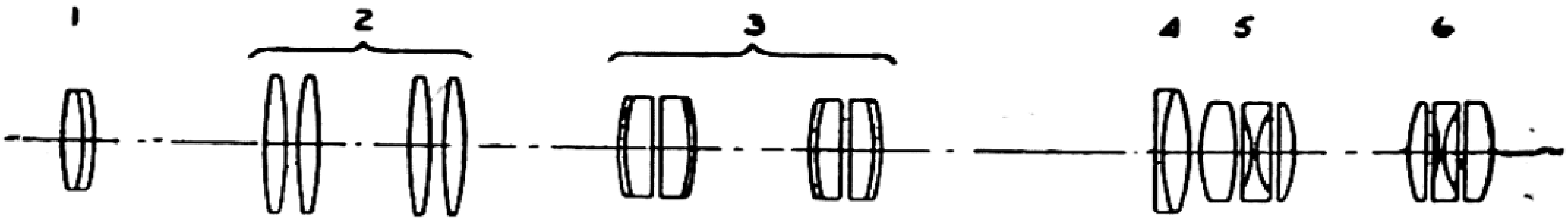

FIG. 2.2. Back's zoom lens system giving a 3 : 1 ratio.

(7) F. G. Back (*J.S.M.P.E.*, **47**, No. 6, Dec. 1946, p. 464) described a lens of complex but novel construction. The operation of the lens is best understood with reference to Fig. 2.2. Components 1, 3, 5 and 6 remain stationary, and components 2 and 4 move as a unit, the distance between them remaining fixed. In this manner the necessity for cams is eliminated. The inventor claims to have found " certain equations and optical relations which permit full compensation with strictly linear displacements of optical components ". This seems to imply the claim that the position of the final image remains exactly constant during the operation of the zoom. It is not difficult to show that such a claim is invalid. The constancy of focus should be superior to that of the Gramatski, the so-called Fokator, system. In fact the success of the system, as regards constancy of focus, seems to depend on the stationary value of T when $M=\pm1$. For, in their mean positions, components 2 and 4 are field lenses ($M=+1$), and component 3 has a magnification roughly equal to -1.

The zoom ratio of this system is 3 : 1. It has a coupled zoom viewfinder, and gives focal length ranges of 17–53 mm. and 35–106 mm. when used with one or other of two interchangeable front lenses.

It is claimed that each lens element has to be corrected for chromatic aberration, spherical aberration and astigmatism, and that coma and distortion are corrected by the " concerted interplay " of the different lenses. There is no mention in the published account of the lens of the manner in which these aberrations remain corrected on varying the image size. Moreover, all the lenses of components 1, 2, 3 and 4 are of positive power, and consequently must have a large positive Petzval sum. Components 5 and 6 appear to be conventional triplet lenses, so that the Petzval sum of these two components would certainly not be less than zero. For this reason it would seem impossible to obtain really good definition over the whole field of view.

(8) R. Cuvillier ("Le pan-cinor et ses applications", *Le Technique cinematographique*, **21**, 73, March 1950) is said to have described an improved system of the Gramatski type. As in the Zoomar lens of Back, two relatively fixed elements move about a stationary lens spaced between them. The lens seems to be a Gramatski system in which the front component is split into two elements, the leading one of which moves with the middle moving lens. With such an arrangement, one would expect the image to be exactly in focus for three magnifications. The defect of focus at other magnifications should also be much smaller than in the Gramatski Fokator system.

The Gaussian Optics of new Symmetrical Systems of Variable Power*

In systems of the Gramatski type the fixed front component produces an image fixed in space. Moreover, if the final image is to remain exactly in focus, the object presented to the rear component must also remain fixed in space. Hence, ideally the object-image distance T for the middle lens should remain constant. If the value of T is correct when the middle lens is in its mean position, it will be too small when this lens is displaced to either side. The focal length of the middle lens needs therefore to be reduced when displaced from its mean position. This can be achieved by constructing the middle component of two elements which move both as a whole and differentially.

Such an arrangement requires the use of non-linear cams, but, against this, it has the advantage that the image remains exactly in focus. Furthermore, it is an easy matter to calculate the effects of errors in the cams and hence to give mechanical tolerances.

Suppose a component of power K to be positioned wrongly by a small amount δX. The defect of focus, measured by the optical path difference introduced at the edge of the aperture, is given by

$$\delta W = \tfrac{1}{2}(u'^2 - u^2)\delta X \qquad (3)$$

where u, u' are the convergence angles of a marginally traced paraxial ray. If $y =$ incidence height of this paraxial ray, then

---

* These systems are the subject of British and foreign patent applications.

$u'-u=yK$, the value of y being assumed to be measured at the principal planes. Hence,

$$\delta W=\tfrac{1}{2}y^2K^2(u'+u)\delta X \tag{4}$$

and the relative aperture yK and the sum of the convergence angles $(u'+u)$ are seen to be the controlling factors. In afocal systems both yK, u and u' are all small, so that such systems have the advantage of not demanding very great accuracy in the cam movements. This being so, it is no great disadvantage to employ non-linear movements. If a component has a relative aperture equal to $F/5$, it is found that

$$\delta W\approx\frac{1}{200}\delta X \tag{5}$$

It is clear that in this case $\delta W=\pm 1\lambda$ leads to $\delta X\approx\pm 0{\cdot}1$ mm., which is very easily attainable.

If the middle components consist of two differentially moving elements it is desirable that they should be of the same focal length. Thus two lenses of powers K_1, K_2 have a combined power

$$K_0=K_1+K_2 \tag{6}$$

when in contact. When spaced apart by a distance d, they have a combined power

$$K=K_1+K_2-d\,K_1\,K_2 \tag{7}$$

The power changes most rapidly when

$$\frac{\partial K}{\partial d}=-K_1K_2$$

has its maximum value. Now $K_1K_2=K_1(K_0-K_1)$, so that

$$\frac{\partial}{\partial K_1}(K_1K_2)=K_0-2K_1 \tag{8}$$

Equating this to zero shows the condition to be

$$K_1=K_2 \tag{9}$$

This result holds for both types of system illustrated in Figs 2.3 and 2.4.

In the present types of system the nodal separation δ in (1) no longer remains constant, since the separation d of the moving element changes. It is well known that the separation of the principal planes of two lenses of powers K_1, K_2, when spaced apart by a distance d, is given by

$$\delta=-\frac{K_1K_2}{K}.d^2 \tag{10}$$

where K=combined equivalent power.

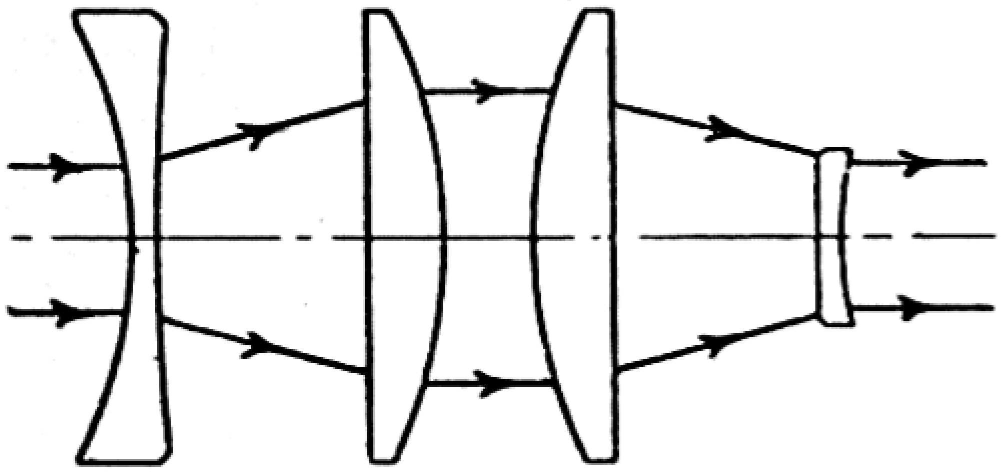

FIG. 2.3. Symmetrical system with positive middle lenses.

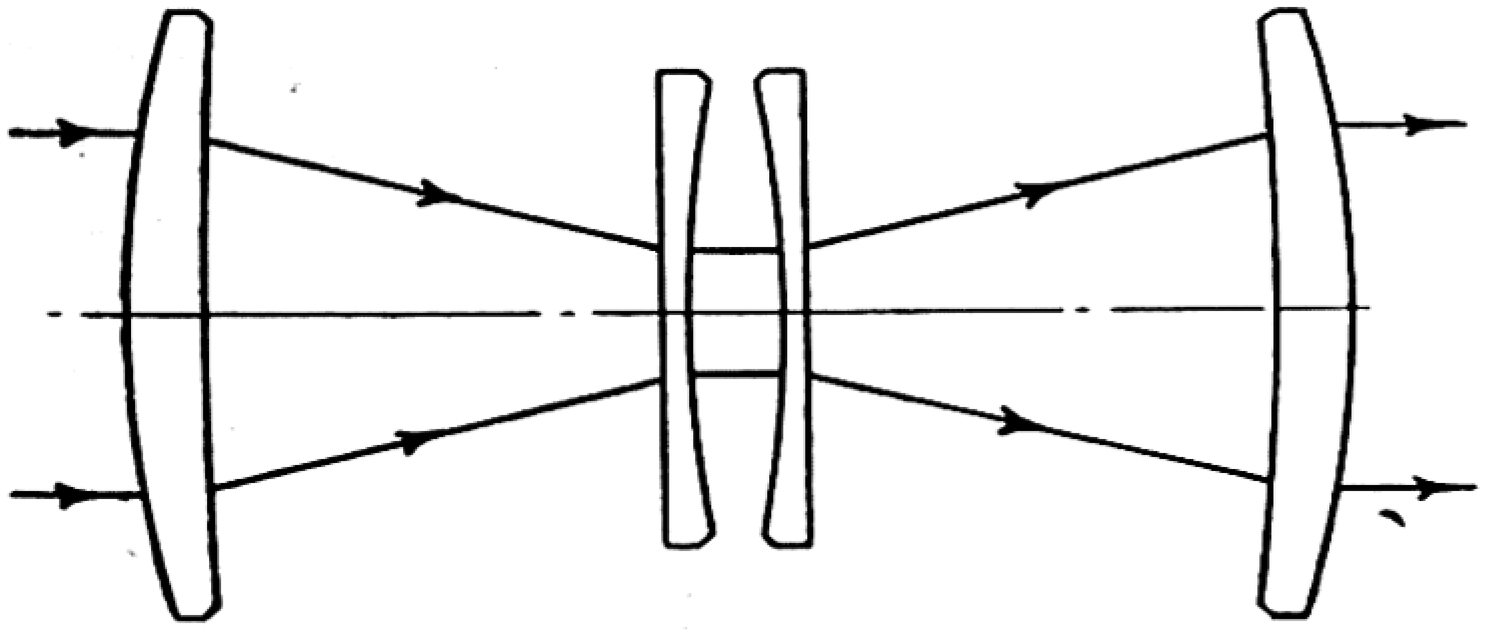

FIG. 2.4. Symmetrical system with negative middle lenses.

When the middle lenses are of positive power (Fig. 2.3), the separation d is decreased when they are displaced from their middle positions. The change in δ is positive and hence the effective object-image distance, $P=T-\delta$, is decreased. In this case, therefore, the change in δ is unfavourable, since it makes necessary a greater decrease in the equivalent focal length of the middle component.

When the middle lenses are of negative power (Fig 2.4), the separation d is increased when they are displaced from their middle positions. The change in δ is again positive, and the change in the object-image distance P is again negative. In this case, however, P is a negative length. Hence the absolute value of P is increased, and the change in δ is therefore favourable, since it makes necessary a smaller decrease in the (absolute) equivalent focal length of the middle component.

When large zoom ratios are involved, the change in δ becomes very significant. For this reason the pos-neg-neg-pos system is to be preferred. An even stronger reason for the choice of this system is the much smaller relative aperture at which each component works. This will be clear from the ray-paths indicated in Figs. 2.3 and 2.4. Moreover, to obtain good axial correction, the front surface of the first component of the neg-pos-pos-neg system needs to be concave to the object. With a stop at the rear of the lens, the principal rays of oblique pencils strike this surface at large incident heights. The distortion so produced is a very serious defect of this arrangement. On the other hand the pos-neg-neg-pos system of Fig. 2.4, not only has a smaller absolute power for the front component, but its shape is also favourable to the correction of distortion.

The above considerations show the most favourable distributions of power to lead to systems of semi-symmetrical type. Furthermore, the movements of the different elements must be symmetrical about their middle position if these movements are to be kept to a minimum. The mechanical tolerances for the cams are found to be practicable. Before considering the aberrations of such symmetrical systems, it is necessary to estimate the defect introduced by an error in the equivalent focal length of one of the moving lenses.

The conjugate distances l, l' of a lens of power K satisfy the equation $(1/l')-(1/l)=K$

The increment in l' due to a small change of power is given by

$$-\frac{\delta l'}{l'^2}=\delta K$$

This corresponds to an optical path difference

$$\delta W=\frac{1}{2}u'^2\delta l'=-\frac{1}{2}y^2\delta K \tag{11}$$

and from this expression the tolerance on equivalent focal length may be found. In terms of $F=1/K$, (11) becomes

$$\delta W=\frac{1}{2}\left(\frac{Y}{F}\right)^2.\delta F \tag{12}$$

For a component having a relative aperture $F/5$, this gives

$$\delta W=\frac{1}{200}.\delta F \tag{13}$$

Putting $\delta W=\pm 1\lambda$, shows the tolerance on focal length to be $\delta F\approx\pm 0{\cdot}1$ mm. This is quite severe, but by no means impossible. Moreover, an error in the focal length of one of the moving lenses can be partially compensated by suitable positioning of these lenses in the initial adjustment of the lens.

In ordinary manufacture it is only the lens thicknesses which lack high accuracy. Since the equivalent focal length of a thick lens is independent of the thickness if one of the surfaces is plane, it is an advantage to make the moving components exactly, or at least very nearly, plano-concave or plano-convex, even when each of these components consist of a compound cemented lens.

One further advantage of the types of construction illustrated in Figs. 2.3 and 2.4 derives from the outer lenses remaining fixed during the operation of the zoom mechanism. Not only does this feature make possible a dust-free and weatherproof mount, but different object or image distances, or both, may be accommodated by merely displacing the appropriate lens to restore the correct object or image distances, or both respectively, for the two moving components. One can then focus on near or far objects and the image will remain exactly in focus using precisely the same cam forms. This is a great advantage for a lens which is intended for use with a ciné or television camera.

What has been said above has related specifically to afocal symmetrical systems having two moving middle components. If a vari-focal lens of finite focal length is regarded as a combination of an afocal system plus a system of finite focal length, and the variation in image size is obtained by causing the magnification of the afocal system to vary, those considerations still apply.

The Correction of Aberrations in Symmetrical Zoom Lenses

If the longitudinal chromatic aberration, the spherical aberration, coma and tangential field curvature of an optical system are all zero, the aberrations of the system are independent of the position of the aperture stop. In the following considerations, the stop will therefore be assumed to be placed midway between the two moving lenses.

In Fig. 2.5 is shown an afocal system of the type having two moving negative lenses spaced between two fixed positive lenses. The three diagrams show the positions of the moving lenses when the magnification is equal to m, 1 and $1/m$ respectively. In each case the stop is shown in the position midway between the two moving lenses.

It will be seen that the $\times 1/m$ system is simply the $\times m$ system reversed. Hence, if the system is corrected for aberration in either extreme position, it will be equally corrected for the other. What is more, the system is perfectly symmetrical at $\times 1$. So that coma, distortion and chromatic difference of magnification are then absent.

To correct the system for chromatic aberration one can choose such dispersive powers for the glass types of components 1, 4 and 2, 3 that the two chromatic aberrations are corrected at $\times m$. The shapes of the pairs of lenses 1, 4 and 2, 3 are then chosen to give freedom from spherical aberration and coma at this magnification. The system will then be free of coma and chromatic difference of magnification at the three positions m, y and $1/m$. To a first order, therefore, these aberrations will be corrected for all positions of the moving lenses. The spherical aberration and longitudinal chromatic

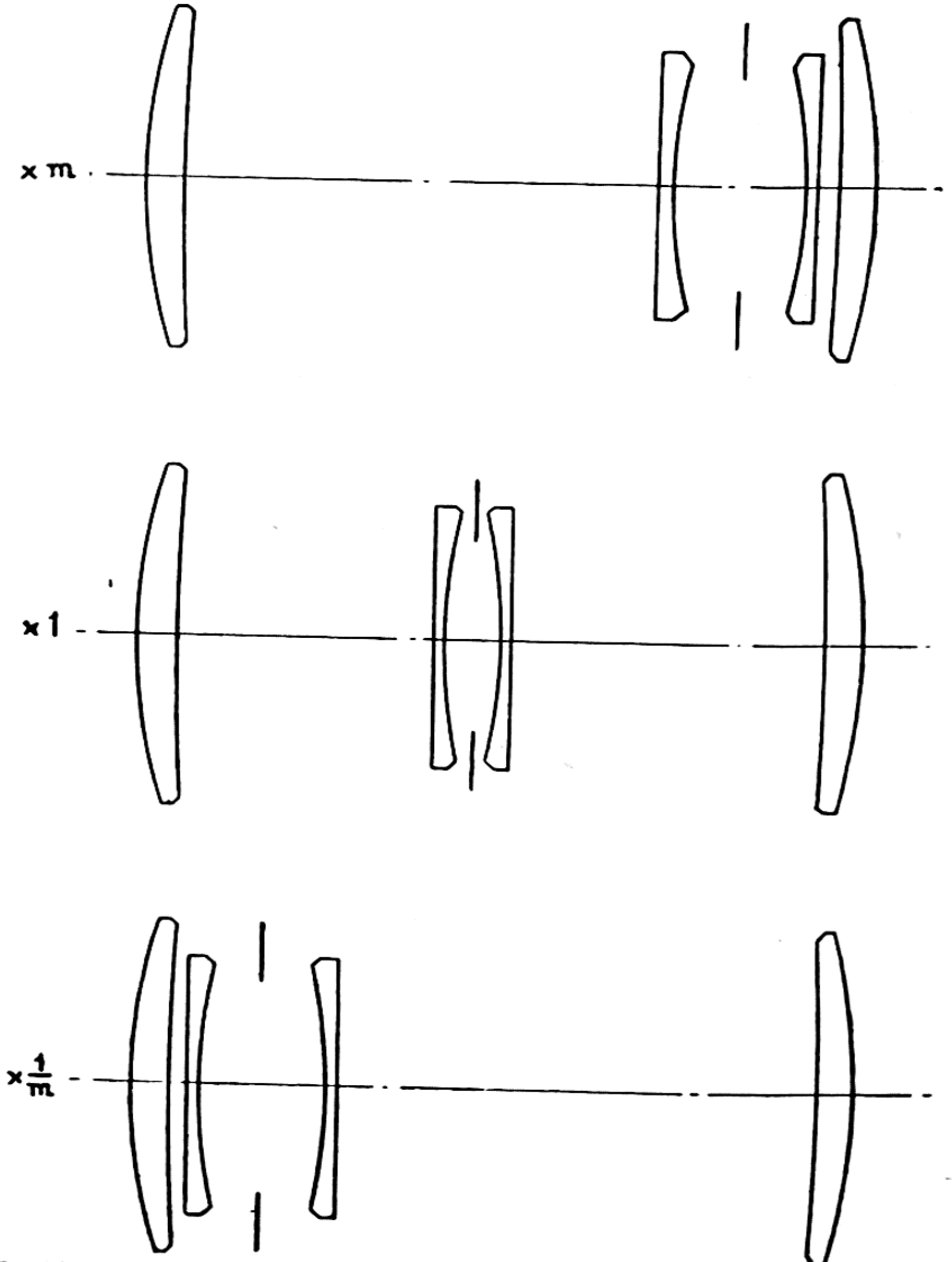

FIG. 2.5. Afocal system having two moving negative lenses, giving magnifications of m, 1, and $1/m$.

aberration will be zero for the magnifications m and $1/m$. For zoom ratios of 2 : 1 to 3 : 1, these aberrations also remain substantially corrected at other positions of the moving lenses.

The astigmatism and field curvature are found to be reasonably well corrected for systems having small zoom ratios, and some control over them can be exercised by a proper choice of refractive index for each of the pairs of glasses. The distortion is zero at ×1, and is fortunately not too severe at other magnifications.

In practice the stop for an afocal attachment is usually that of a fixed focus camera lens placed behind it. This results in a less well corrected system, due to the introduction of significant higher-order aberrations. Nevertheless, such systems have been successfully made, and are now in regular use for outside broadcasts by the B.B.C. Television Service. These systems work with camera lenses up to 2″ (50 mm.) in diameter and angles of field of 30°.

The stability of the aberrational correction in these systems is insufficient when larger zoom ratios are contemplated. For the design of a 5 : 1 variable power system, therefore, a slight increase in complication was found to be necessary. Each of the four components was made separately achromatic in order to give stability to the correction of the chromatic aberrations.

It then seemed possible to propose a method of very general application in variable power systems. It is known (H. H. Hopkins, 'Wave Theory of Aberrations', Oxford 1950, p. 110) that the astigmatism of a system of aplanatic thin lens components depends only on the sum of the absolute powers of the different elements. It is independent of both the spacings of the lenses, the position of the stop and the object distance. It proves, however, impossible to realise such a system, for it can be shown that the coma of a system of thin lenses in contact is a linear function of the object distance, whose gradient is little influenced by the precise construction of the system. Hence any one component will be aplanatic for only one magnification. At any other magnification it has very substantial amounts of coma, and both the correction of this aberration and the constancy of the astigmatism are lost. This result is proved below.

The coma of any thin lens may be expressed (see Hopkins, *loc. cit.* p. 126) as

$$S_{\mathrm{II}}=\frac{1}{2}Hy^2K^2\left(\frac{\mu+1}{\mu(\mu-1)}.\,X-\frac{2\mu+1}{\mu}.Y\right) \tag{14}$$

where $H = Nu\eta$, a constant for the system ; and X, Y are variables denoting the shape of the lens and the position of the object respectively. For a system of thin lenses in contact,

$$S_{\mathrm{II}}=\tfrac{1}{2}Hy^2\Sigma K^2\left(\frac{\mu+1}{\mu(\mu-1)}.\,X-\frac{2\mu+1}{\mu}.Y\right) \tag{15}$$

the summation being taken over all lenses. If now the object distance is changed by an amount measured by δY, the change in S_{II} is

$$\delta S_{II} = -\tfrac{1}{2} H y^2 \Sigma K^2 \left(\frac{2\mu+1}{\mu}\right) . \delta Y$$

Now the variable Y is defined by $Y = (u' + u) / (u' - u)$ with an obvious notation. Since, for any element, $u' - u = yK$, it follows that $yK \delta Y = 2\delta u$, where δu is the change in the initial convergence angle due to the change in the object-distance. Thus, the change in coma on changing the object position is given by

$$\delta S_{II} = -\delta u . H y \Sigma \left(\frac{2\mu+1}{\mu}\right) K \qquad (16)$$

The factor $(2\mu + 1)/\mu$ only changes from 2.71 to 2·59 on increasing μ from 1·40 to 1·70. Hence, it will be very nearly the same for any glass type used. It is now easily seen that a system of thin lenses in contact will be corrected for coma for only one position of the object ; and that, at other positions of the object, the coma present will be but little affected by the precise arrangement of lenses employed. In practice the coma which is found is very large.

Since a system of separately aplanatic components will not yield stable correction of aberration, it is again necessary to recourse to a symmetrical construction, in which the change in coma in one of the moving components is compensated by a change in coma of the other moving component. It may be noted in passing that a zoom lens must have the object-distance changed for at least two of the components if stable correction of coma is to be achieved.

Such a lens, having a zoom ratio of 5 : 1, is shown in Fig. 2.6. The moving components 2 and 3 were designed to be free from spherical aberration and coma at a magnification of × 2. This can be arrived at since glass types and lens shapes give two degrees of freedom. The outer components 1, 4 of the afocal part of the system were designed to be separately aplanatic, since for these the object and image distances remain unaltered.

From what has been said above, it will be clear that the coma of such a system, together with the chromatic aberrations, will remain perfectly corrected for all positions of the moving lenses. Furthermore, the spherical aberration will be zero at × 2 and × $\tfrac{1}{2}$, and it will change but slowly with the object distance, since the sine condition is satisfied (there being no coma) and the convergence angles are small. In this case Herschel's condition is very nearly satisfied, and is exactly satisfied in the middle position. For this reason the correction of spherical aberration is relatively stable. In a 5 : 1 system, the spherical aberration was found to vary parabolically between the limits ±2λ.

By a suitable choice of refractive indices and dispersions for the glass types of the moving components it is possible to ensure that the astigmatism does not change too much between the × 2 and × 1 positions. The distortion is also found to be small at × 2. The residual negative astigmatism and field curvature of the afocal system thus remain reasonably constant and are corrected by means of the cemented doublet 5.

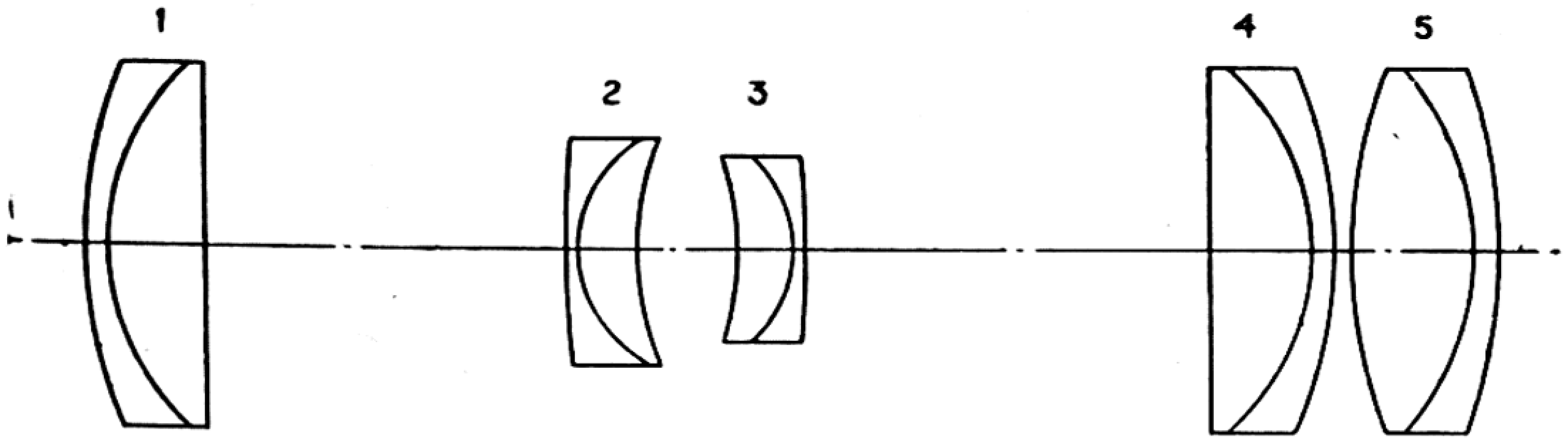

FIG. 2.6. Zoom lens system with correction for aberration and coma. Zoom ratio 5 : 1.

The stability of the astigmatism correction is still not comparable with the excellent correction obtained for spherical aberration and coma. Work continues in an attempt to improve the correction of astigmatism.

Mechanical considerations make it impossible for the 5 : 1 zoom lens described to work at large relative aperture when the longer focal length region is employed. For this reason the relative aperture of the lens in question remains constant at f/3 for the range of focal lengths 4″–9″, and it decreases linearly to f/6·3 as the focal length changes over the range 9″–20″.

It is found convenient in a zoom lens of this size to arrange for the iris diaphragm to remain fixed to the rear of component 3, and to move with it. Since to conserve a constant aperture ratio requires only that the rim of the diaphragm should follow the edge of the cone of the axial pencil diverging from 3 to 4, a simple mechanical linkage has been found capable of controlling the size of the diaphragm opening.

(6) Acknowledgements

It is a pleasure to acknowledge my gratitude to the Directors of Messrs. W. Watson & Sons, Ltd., who are manufacturing these new systems, and to Mr. J. Mangan of their Research Staff for his constant assistance in this work.

SOMMAIRE SUMMARY

Une étude rapide des solutions anciennes est suivie d'une description d'un nouveau système répondant à certain conditions de symétrie. Une système de distance focale finie peut être considéré comme l'association d'un systeme de distance focale constante et d'un système afocale de grossissement variable dans certaines limites.

La variation de la grandeur de l'image est obtenue par un déplacement convenable des deux composantes internes de la partie afocale du système. On montre qu'il est advantageux pour ces composantes d'avoir la même distance focale négative et un grandissement égal à —1 (pour l'ensemble) dans la position moyenne. Les tolérances optiques sont précitées ; elles montrent quelle précision il faut atteindre dans le mouvement des deux lentilles négatives.

La stabilité de la correction des aberrations est etudiée et l'on montre comment les considerations relatives aux conditions d'Herschell et d'Abbé conduisent a un système dans lequel le système téléscopique est complètement symetrique dans la position moyenne des éléments mobiles. On décrit un système pour lequel la variation relative de convergence est égale à 5 : 1.

A brief review of earlier systems of variable power is followed by an account of the development of a new system which fulfils certain conditions of symmetry. A system of finite focal length is regarded as a combination of a telescopic system, whose magnification may be varied within desired limits, followed by a system of fixed focal lengths.

The variation of image size is achieved by suitable displacements of the two inner components of the "telescopic" part of the system. It is shown to be advantageous for these inner components to have equal negative powers and to have a magnification equal to minus 1 in their mean position. Optical tolerances are given showing the required accuracy of the movements of the two moving components.

The stability of the correction of the aberrations is investigated, and it is shown how considerations of the sine condition and Herschel's condition lead to a system in which the telescopic system is completely symmetrical in the mean position of the moving parts. Such a system is described having a variation of power of 5 : 1.

3. A New High Aperture Photographic Objective having a Spherical Field

A. WARMISHAM
(Taylor, Taylor and Hobson, Ltd., Great Britain)

TO a mind which can see through and beyond technical detail, the most astonishing thing about the Schmidt objective is its simplicity. Everyone knows today that its two elements are sufficient to achieve its purpose ; everyone knows the optical theory necessary to prove this fact. I believe it is widely realised that there is more in the Schmidt than the underlying construction, that it is in fact a work of art in the classical sense of that frequently mis-applied term.

This view is reinforced by a survey of those objective designs of the last 20 years intended to increase the aperture to f/1·4 or f/1·0, with a flat field of 20° semi-angle. Even when advantage was taken of the new high index glasses, it was found necessary to increase the complexity of some constructions to include 10 air-glass surfaces, so that although the reflection reducing coating had become widely used and was in general highly efficient, the overall transmission was of the order 80% to 85% of the incident light. Many such constructions had to be restricted to short focal lengths both on account of material defects and also because of the magnitude of outstanding aberrations.

A detached survey of those developments set beside the Schmidt suggested that the elaboration was ill-advised and inevitably led to the conclusion that the root cause of the complexity is due to the tradition of flattening the field. If we may allow the objective to be corrected on a spherical field, we shall have a simpler and better lens than the conventional flat field one.

The first efforts to achieve a spherical field reported from the U.S.A. and France were concerned with the further elaboration of the Petzval type of lens. Like many of the old lenses, the astigmatism of these was quite suitable for correction on a curved field concave towards the lens. Thus the starting point of this work was established and the direction in which improvements were to be found could be fairly easily discovered.

When we examined the problem afresh with the example of Schmidt in mind, it seemed a simple thing to substitute for Schmidt's convergent mirror a convergent objective corrected for coma and astigmatism with respect to the same stop. The original design of this type was made by Cox in 1946 and he called the construction the Dioptric Schmidt. Like the Schmidt, this lens consists of a front aspheric member of relatively low converging power, somewhat widely separated from a rear convergent achromatic member which is corrected for coma and astigmatism with respect to a stop situated at the aspheric member. Exactly like the Schmidt mirror the rear member is heavily undercorrected for spherical aberration and for field curvature, and, to complete the analogy, the aspheric surface of the front member balances the spherical aberration of the back, and the uncorrected field remains uncorrected. In these objectives the field is always concave toward the lens.

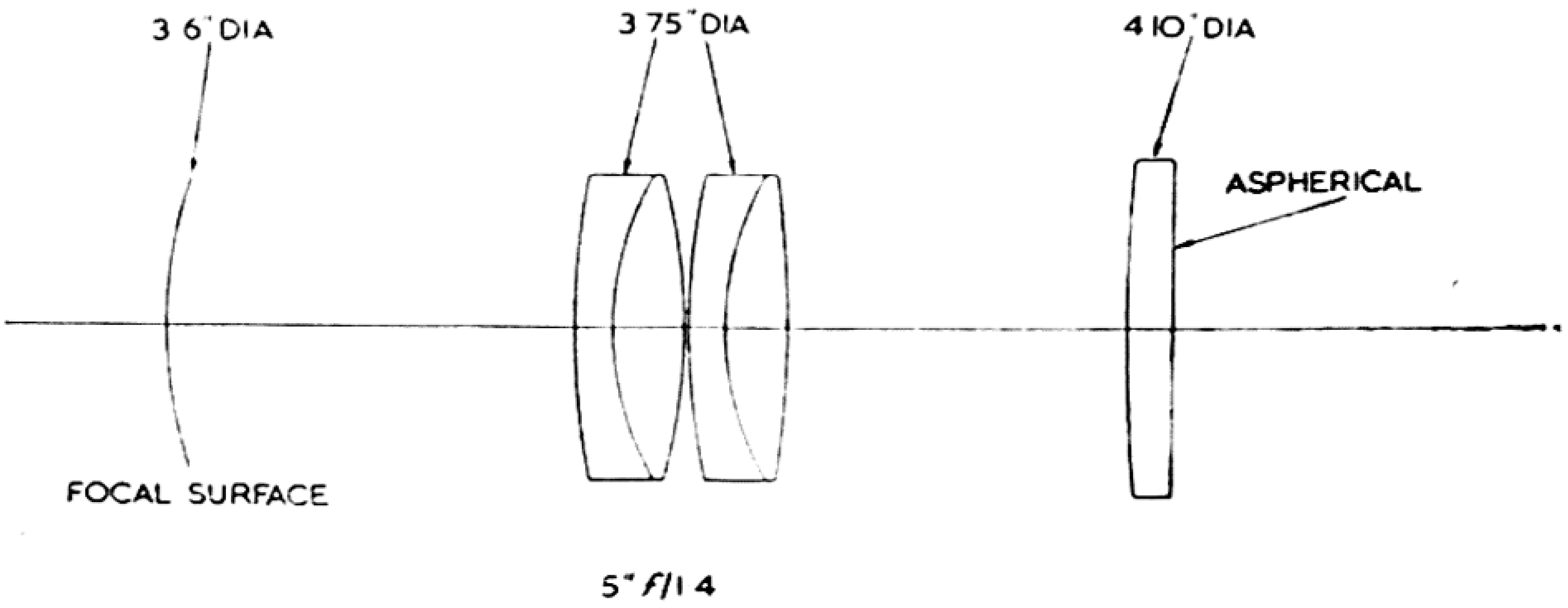

FIG. 3.1. "Dioptric Schmidt" lens constructed by Cox.

In his original construction, Cox [1] produced a well corrected f/1·4 lens using a pair of doublets in the convergent member (Fig. 3.1). The semi-angular field is 18°. Although the lens contains five elements, one of which is an aspheric, it compares favourably in complexity of construction with any f/1·4 of similar angular field and similar definition. It is designed for magnification 7·5.

The early constructions had all been regarded as projection lenses and the tests were all visual. It was realised that unless they could be used for photography the applications of these objectives would be rather restricted. It appeared that in radiography the use of high apertured objectives would be welcomed.

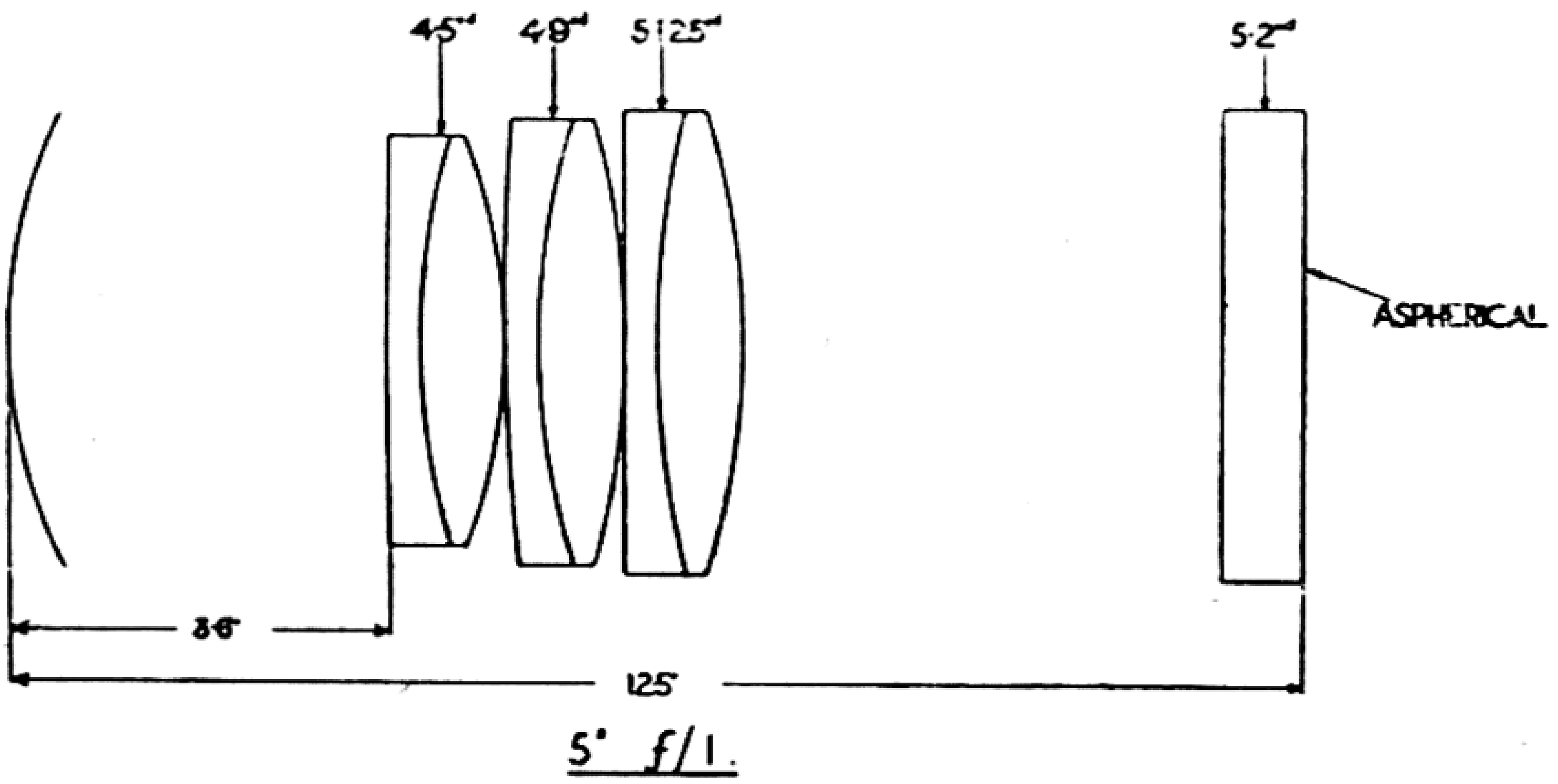

FIG. 3.2. Objective for photographic use, employing three doublets.

In a later construction intended for photographic use, by using three components in the rear member we were able to produce satisfactory results at the aperture f/1·0. The first f/1·0 design[2] used three doublets in the back (Fig. 3.2). It is designed for magnification × 6·4, the focal length is 5" and it has a semi-angular field of 22½°. It shows some residual distortion, which fortunately is no serious handicap in radiographic work. Apart from the distortion, the most significant residual aberration is the secondary spectrum, which however in applications to radiographic work does not seriously depress the resolving power, because of the limited colour sensitivity of the film. In all these designs the aberrations are calculated using NF and in establishing the achromatism, both longitudinal and oblique, the interval *e–g* is used.

A still more recent construction[3] which differs from the f/1·0 construction in an improved distribution of the convergent power in the triplet and by an increase of one in the number of optical elements is shown in Fig. 3.3. By this means it is possible to increase the aperture to f/0·7.

An alternative construction for an objective of f/0·7 is shown in Fig. 3.4. The outline certainly does resemble a well known type of microscope objective. I think there is little doubt that this form may yield an aperture of f/0·6, with a semi-field of 16°, but this is not yet an accomplished fact.

In order to make photographs with these objectives, one must provide means of locating the film in the proper spherical surface during the exposure.[4] Fig. 3.5 shows the register plate in position. The sensitive side of the film is pressed against the convex spherical surface of the register plate by a concave pressure plate of similar radius of curvature, which is brought into contact by a toggle movement. In order to demonstrate the mechanical possibility of providing satisfactory mechanism for controlling the film position and shape, a primitive specimen of a device containing all the essential features was made and successfully used to produce photographs of the radiography screen on 70 mm. film, which showed very good

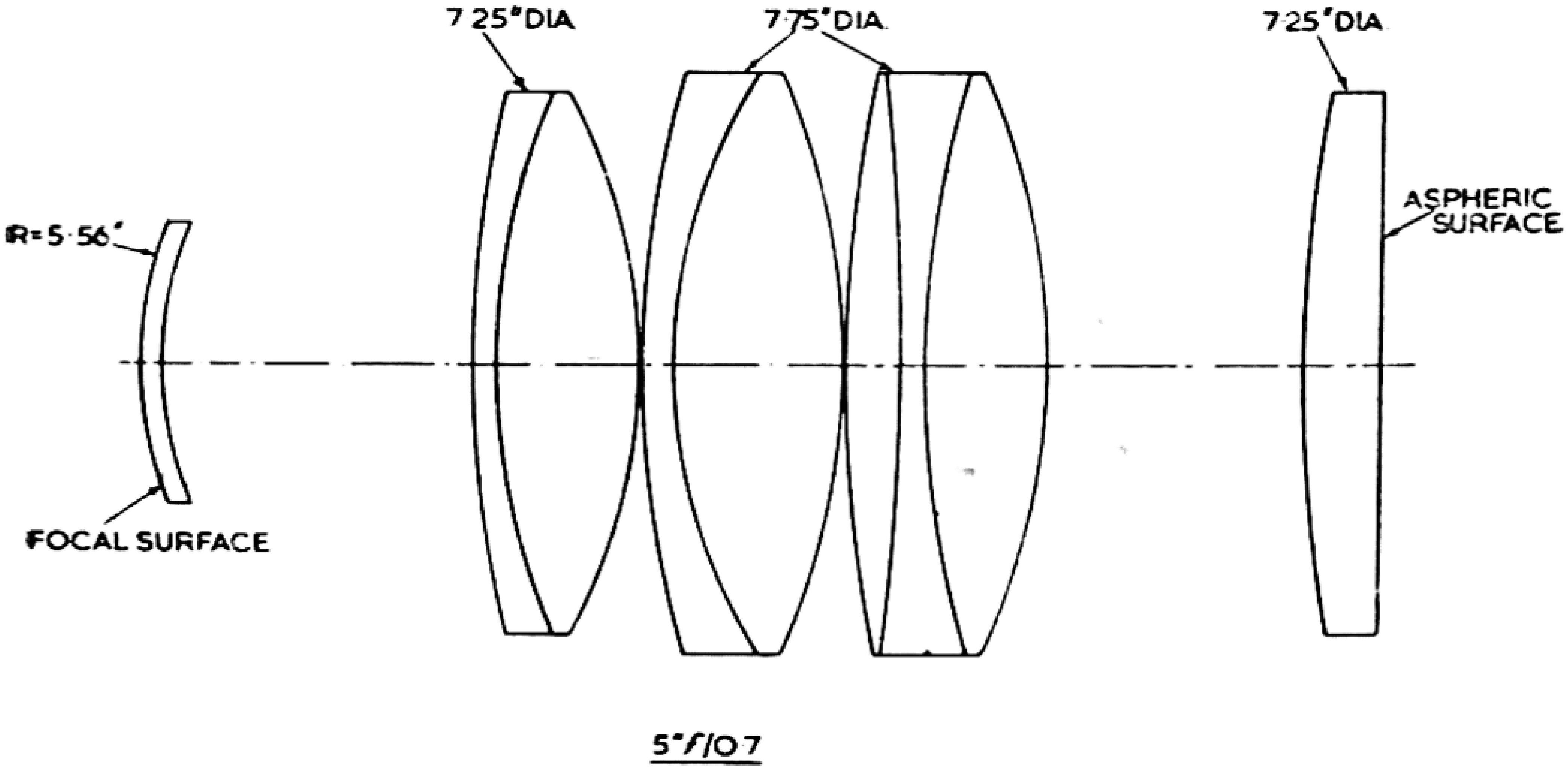

FIG. 3.3. More recent construction with extra optical element.

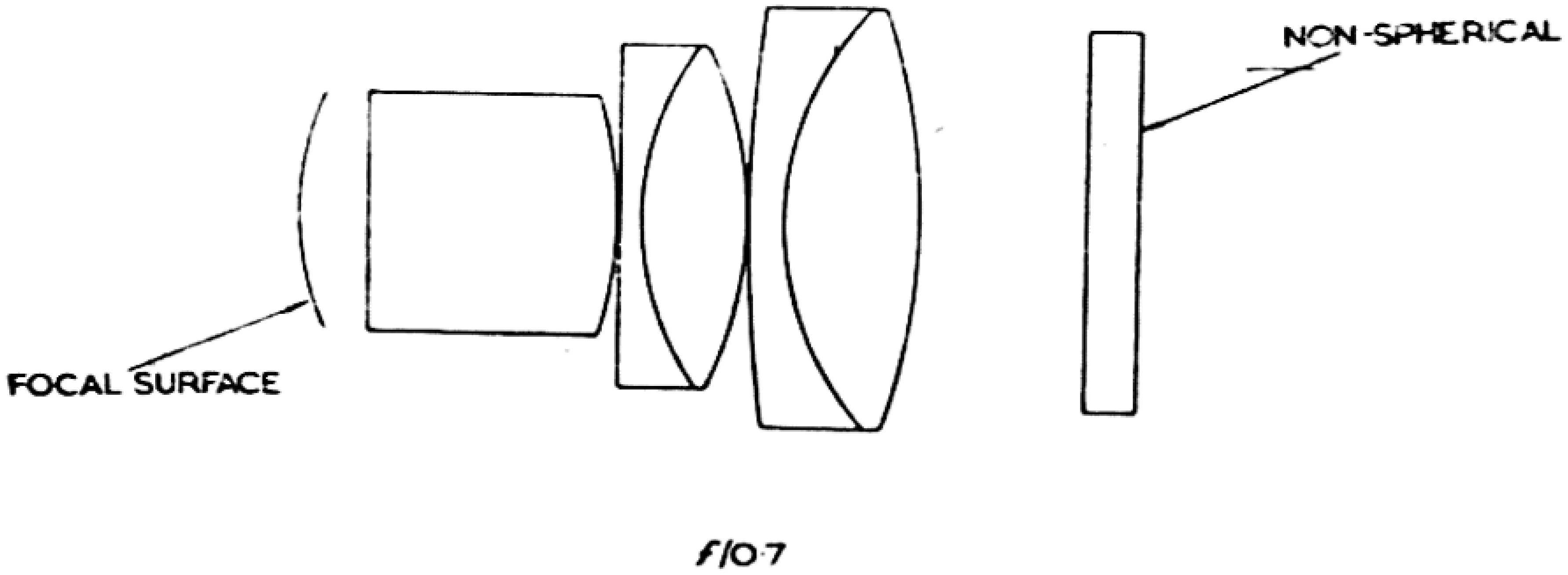

FIG. 3.4. Alternative construction giving an objective with f/0.7.

resolution. The credit for initiating the solution of this problem is due to Wreathall. In a laboratory test of the 5″ f/1.0 the resolving power was 20 to 30 lines per millimetre over the entire field.

We are now in a position to indicate why we decided to apply these dioptric constructions for radiography in preference to the classical Schmidt. We are planning to use the 5″ focal length for 70 m/m. film and a 2″ focal length for 35 m/m. film. With either focal length the camera would obscure the incident light in a mirror Schmidt system, whereas with the dioptric objectives, all the camera apparatus is confined to the rear and there is no obstruction. In astronomical work it is the very much larger focal lengths used which makes it possible for the camera to be placed in front of the objective without causing unacceptable obstruction.

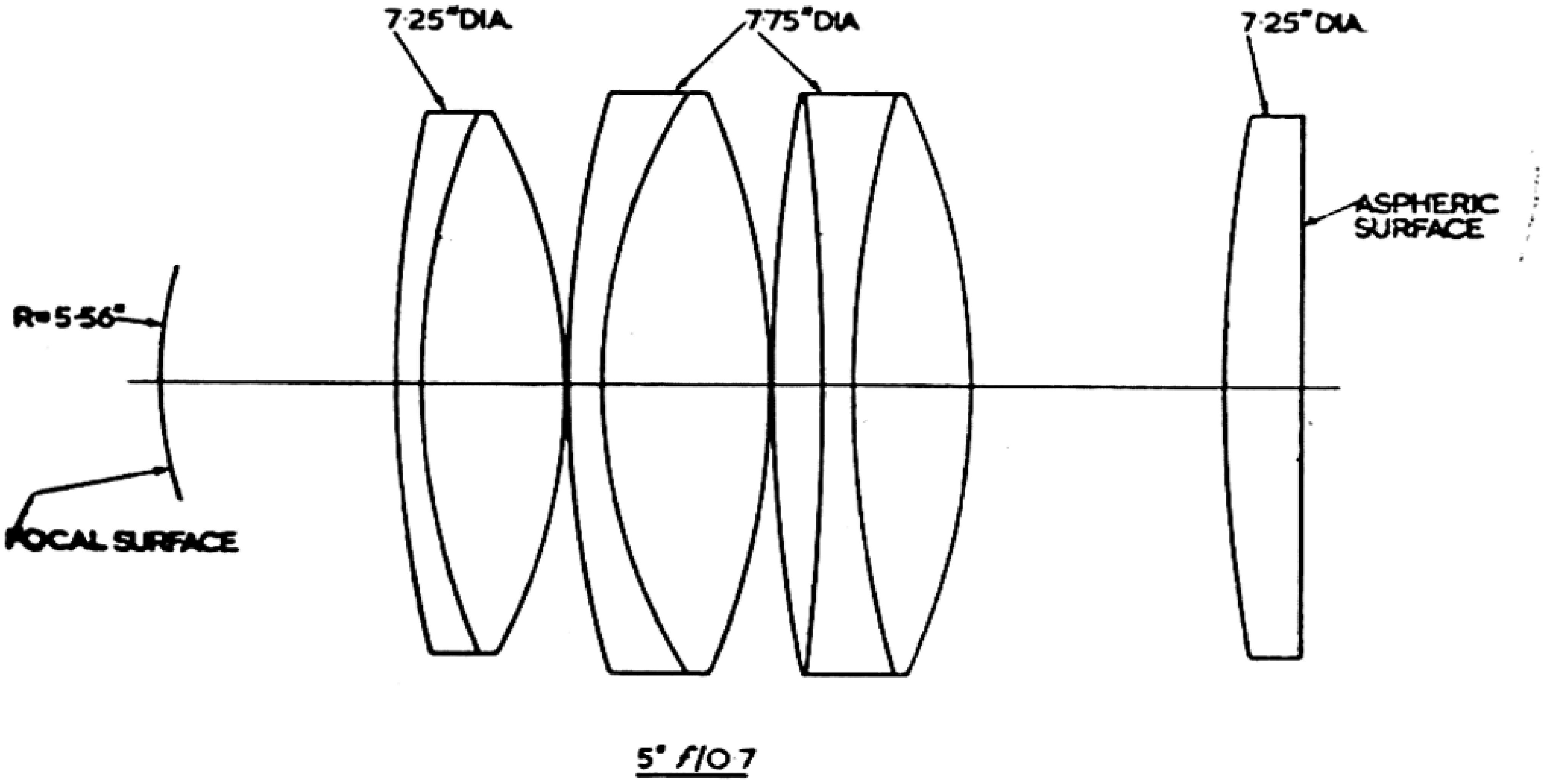

FIG. 3.5. Method of locating the film in the spherical surface.

A convenient means of providing a critical visual test of the performance of these objectives is illustrated in Fig. 3.6. On the left is a concave spherical surface accurately ground in glass to the curvature of the image field of the lens, conjugate to a flat objective field at the specified magnification. Preferably the concave surface is painted dull black and on it are cemented steel bearing balls: we usually use balls $\frac{1}{32}$″ diameter. A light source as indicated, and a flat screen away to the right complete the equipment. An instructive test is to focus the lens in white light, and then, on inserting a green filter near the light source, to observe that this causes a reduction of the spot size by a factor larger than 2.

Fig. 3.7 shows the data used by the designer to determine the best field curvature in the f/1·0 lens. Taking the pole of the aspheric surface as the stop centre, five principal rays were calculated and the astigmatism residuals determined. The table on the left shows the positions of the sagittal and tangential foci relative to the paraxial focus at the short conjugate. The table on the right shows the positions relative to a sphere of radius 1·250 drawn through the paraxial focus. It is clear that limiting our consideration to a semi-angle of 22½°, the sphere of radius 1·250 is the best result one can get out of this calculation. For comparison, the radius of the Petzval surface is 1·296. It is reasonable to suggest that in these lenses, the probability is that the higher order astigmatism will be undercorrected as illustrated in this example, and that therefore the radius of the preferred image sphere will generally be somewhat shorter than that of the Petzval surface.

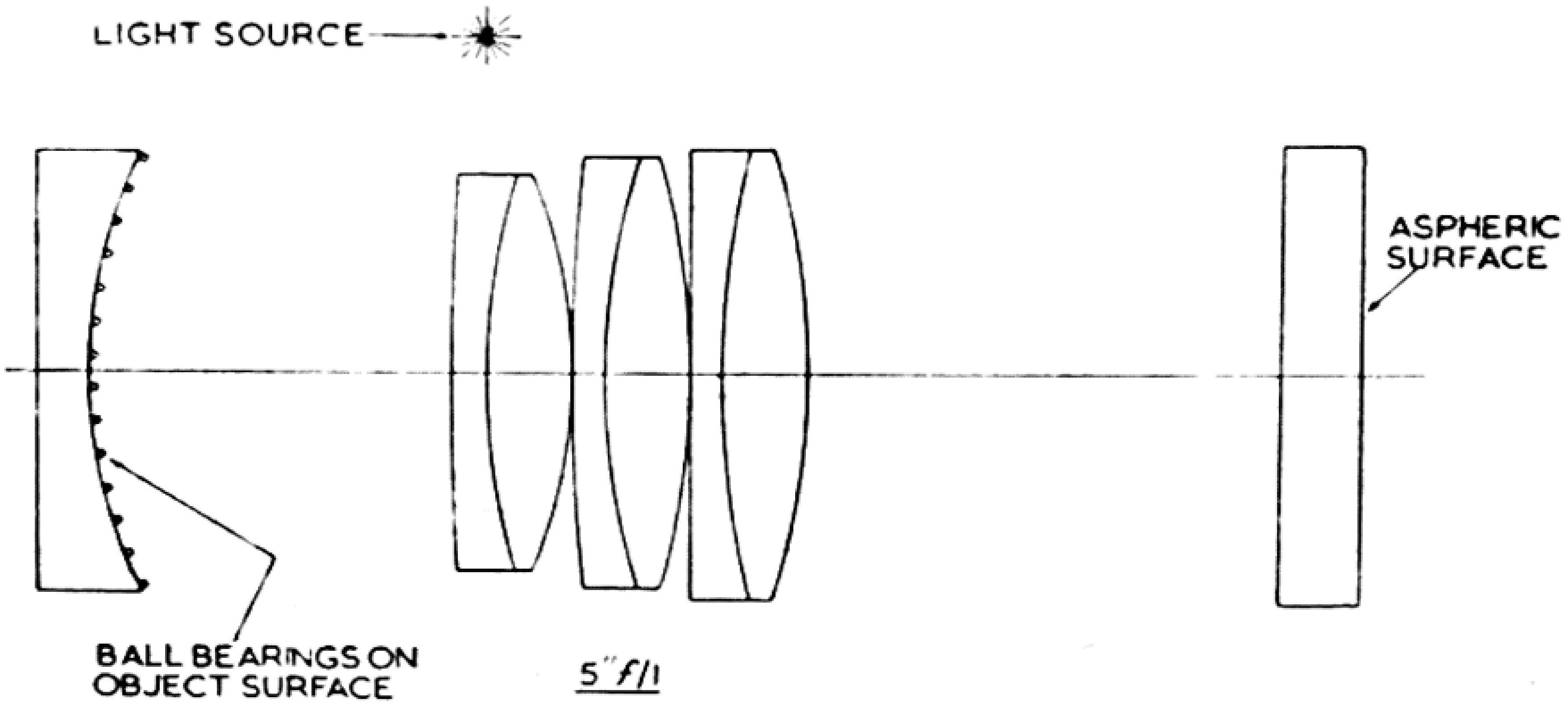

Fig. 3.6. Critical visual test for the performance of the objectives.

I want next to describe a labour-saving method of calculating an aspheric profile, which is applicable when the aspheric is an end surface of the system, as it always is in these objectives, and when both conjugates are finite.

At this stage of the calculations, the total available information about the system is (1) the focal length and the magnification, and the positions of the conjugate focal surfaces; (2) through the stop centre which is the pole of the aspheric, five principal rays have been traced and the astigmatism residuals are suitably small; (3) the first order spherical, chromatic, coma and astigmatism residuals are all known small quantities and (4) the paraxial curvature of the aspheric.

Our object is to determine the equation for the plate profile in the form

$$X=a_2y^2+a_4y^4+a_6y^6+a_8y^8$$

			R 1·250	
	δs	δt	δs	δt
22½°	−·05790	−·05725	−00098	−·00033
20°	−·04597	−·04554	−00022	+·00021
17½°	−·03537	−·03509	+·00020	+·00048
15°	−·02614	−·02595	+·00033	+·00052
12°	−·01687	−·01668	+·00030	+·00049

FIG. 3.7. Table for use in determining field curvature. Radius of Petzval curvature 1.296; Equivalent Focal Length 1.000.

In Fig. 3.8 the surface $n-1$ is the inner spherical surface of the plate and the surface n is its outer aspheric surface. In addition to the paraxial ray we need a zonal ray traced backwards from the short conjugate axial focal point. The paraxial ray can be completed and the zonal ray can be brought through the surface $n-1$. Q is the unknown point where the zonal ray meets the aspheric

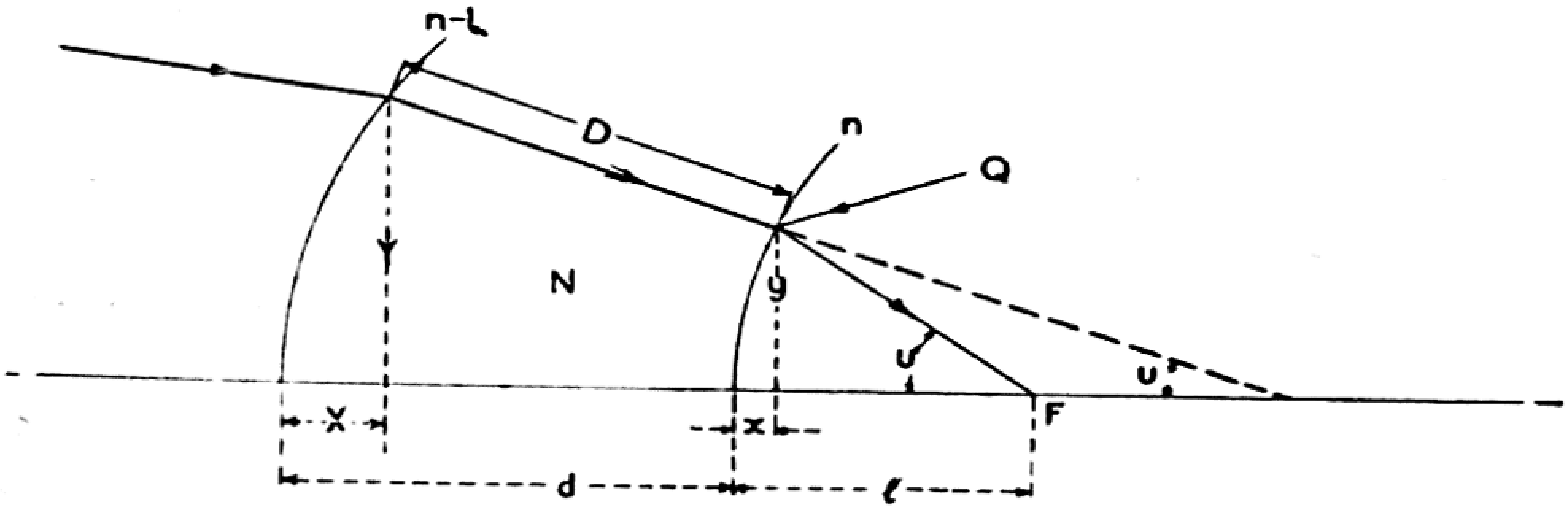

FIG. 3.8. Figure for determining the equation for plate profile.

surface and F is the known paraxial focal point in the notation of the figure. The length D, the co-ordinates x,y of Q and the angle of U^1 are all unknown. N is the refractive index of the plate.

From the figure $x=X-d+D\cos U$ and $y=Y-D\sin U$ so that $QF^2=(Y-D\sin U)^2+(Z-D\cos U)^2$ where $Z=l^1-X+d$. Hence equating the zonal and paraxial optical paths

$$p=P+ND+[(Y-D\sin U)^2+(Z-D\cos U)^2]^{\frac{1}{2}}$$

a quadratic in which D is the only unknown. Solving for D we can then evaluate x and y, and from these $\tan U^1 = y/(l^1 - x)$, and then $\tan I = \dfrac{\sin(U^1 - U)}{\cos(U^1 - U) - N}$ giving I. This leads to $\dfrac{dx}{dy} = \tan(I + U)$.

If the value of U^1 derived above gives a satisfactory value of the sin condition we can now proceed to calculate the unknown coefficients in the equation for the plate profile.

Now we know a_2 from the paraxial curvature of the surface n and from the first order calculation of the spherical aberration we get the value of a_4. So we can compute :

$$a_2 y^2 + a_4 y^4 = x_1 \text{ say and } 2a_2 y + 4a_4 y^3 = V_1 \text{ say}$$

Next it follows that

$$a_6 y^6 + a_8 y^8 = x - x_1 = q \text{ say}$$

and

$$6a_6 y^5 + 8a_8 y^7 = \frac{dx}{dy} - V_1 = V \text{ say}$$

in which all the quantities on the right have been found and therefore

$$a_6 = \frac{8q - Vy}{2y^6} \text{ and } a_8 = \frac{Vy - 6q}{2y^8}$$

completes the equation of the plate profile.

As a general check the trace of the zonal ray is completed trigonometrically.

Now to go back a step, if the value of U^1 does not show a satisfactory correction of the sine condition, the practice is to bend the plate slightly to correct the defect and then to repeat the calculation of the profile.

It is found that if the zonal ray is calculated for about 0·83 full aperture the four-term equation for the plate profile gives satisfactory results for apertures not exceeding f/1·0.

These developments which I have briefly reviewed, are lineal descendants of the Schmidt. On looking over the developments in optical objectives in the last 50 years, I draw a close parallel between the influence exerted by Schmidt on the minds of present day opticians and the similar influence exerted by Dennis Taylor on previous generations. Both Taylor and Schmidt stood out above their contemporaries and both produced objectives of magnificent simplicity. The fundamental ideas underlying Taylor's work were quickly seized and digested by the optical community and many famous objectives designed in the first half of the century were descendants of the "Cooke" Triplet. Similarly, Schmidt's work is now widely understood, and it seems very likely that the near future will see a rapid development of more descendants of the Schmidt.

REFERENCES

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[3] Wreathall, W. M. : Application No. 17818/50 ; U.S. pending.
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SOMMAIRE

SUMMARY

Un nouvel objectif d'ouverture f : 1 et dont le champ est sphérique destiné initialement à la radiologie a été récemment proposé. L'objectif consiste en un groupe arrière d'éléments convergents situés à faibles distances les uns les autres et d'un élément antérieur peu convergent possédant une surface aspheriqué. Le rayon de courbure de champ est d'environ 1 fois 1/u la distance focale. Une bonne résolution est obtenue dans un demi-champ angulaire de 18°. La construction en est décrite. On indique également une modification ultérieure du même type d'objectif permettant d'atteindre l'ouverture f : 0·7 et les moyens adéquats pour contrôler ces objectifs.

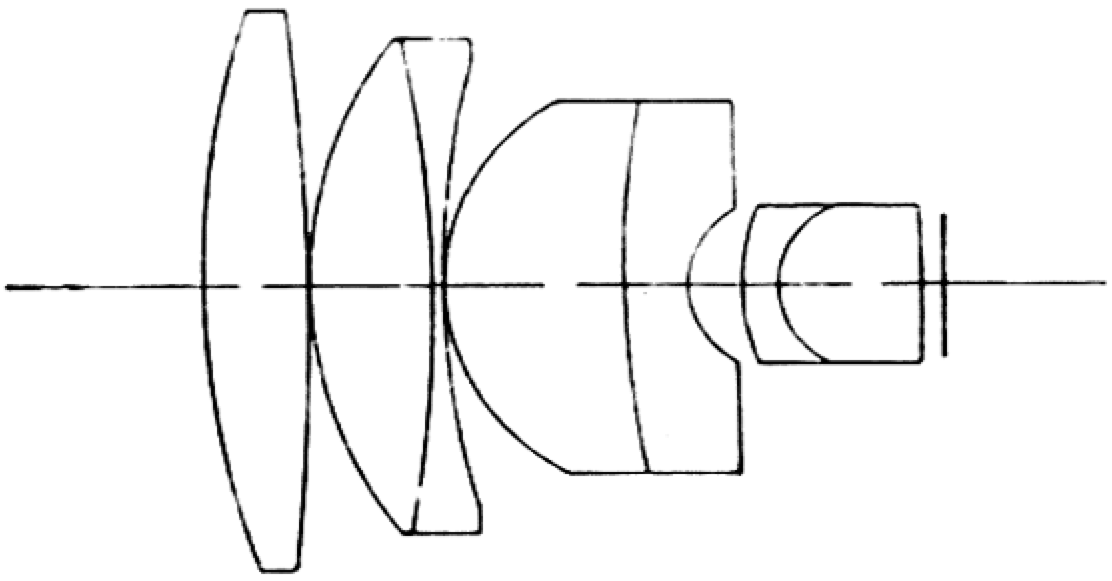
A new objective having an aperture f/1 and a spherical field, and intended primarily for radiology, has recently been introduced. The objective consists of a closely packed rear group of convergent members and a weak front member having an aspheric surface. The radius of the spherical field is about 1¼ times the focal length. Over a semi angular field of 18° high resolution is obtained. The construction is described and illustrated.

The paper also describes a further development of the same type of objective to give an aperture f/0.7, and convenient means of testing these objectives.

DISCUSSION ON PHOTOGRAPHIC LENSES

Mr. C. G. Wynne. The new high index glasses are often of considerable value, as Mr. Kingslake has said, for the reduction of higher order aberrations in photographic lenses, this reduction arising from the smaller curvatures that are required to give the same optical power. This method is primarily of value in the simpler types of lens, where the parameters at the designer's disposal are too few to allow of a systematic balancing of higher order aberrations of opposite signs in the complete system. Where this latter possibility exists, for example in lenses of double-Gauss ("Planar") form, high index glasses may in some cases react adversely on the corrections by reducing curvatures and angles of incidence in parts of the lens where high values are desirable to secure higher order aberration balance.

The possibility of systematic higher order aberration correction may be illustrated by work we have carried out on the double-Gauss type of lens. Earlier work, referred to by Mr. Kingslake, has shown how the oblique spherical aberration common to this form of objective may be corrected, for example at a relative aperture of f/2[1]. More recent work[2] has shown that for rather smaller relative apertures (from f/3.5 to f/5.0) this correction of oblique spherical aberration may be combined with the balancing of the fifth order astigmatism and field curvature against the still higher orders. Figure 1 shows the form of the sagittal and tangential field shapes for two such lenses; for unit focal length the Petzval sums are 0.06 and 0.05.



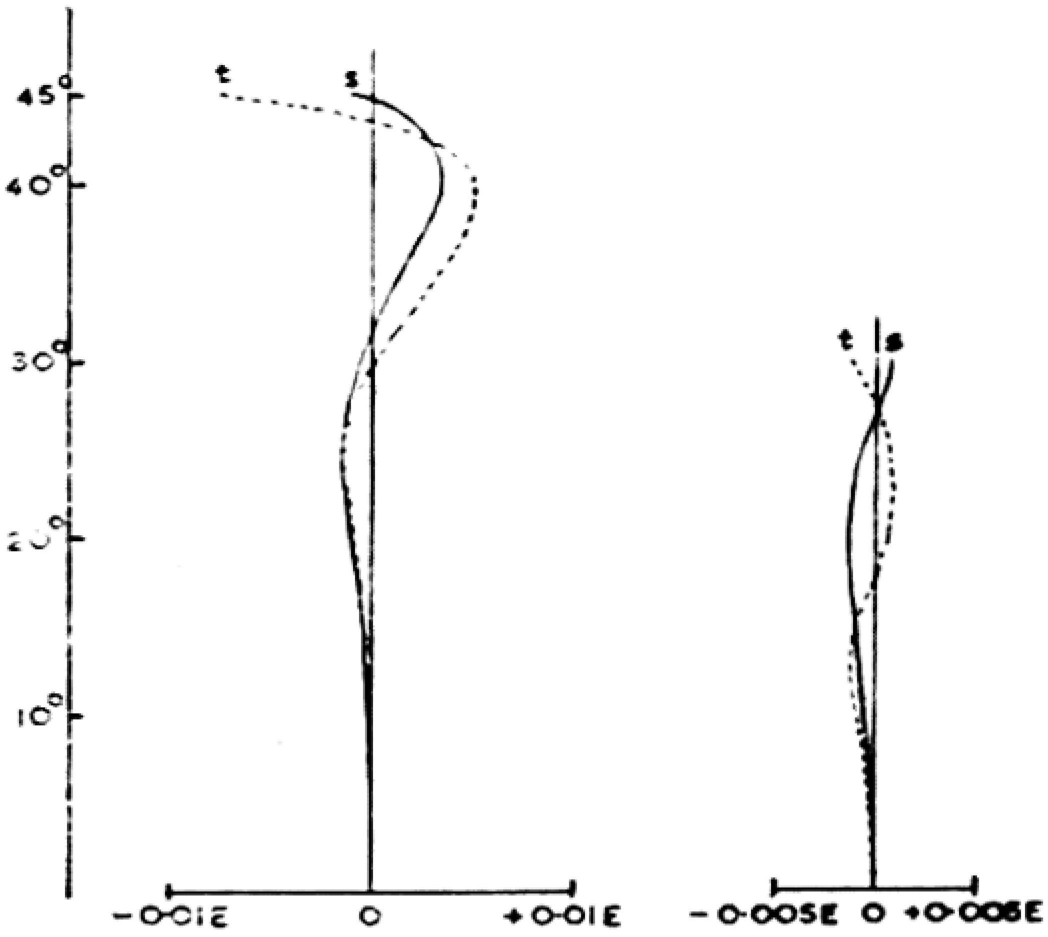


FIG. 1 (right). Field shapes for two double-Gauss lenses.
FIG. 2 (above). Typical wide aperture lens.

We have also been working on the problem of very wide aperture lenses which Mr. Warmisham has discussed, using a different approach which dispenses with the need for aspheric surfaces and enables the lens to be corrected over a flat image surface[3]; these lenses are being designed for rather high speed cine-radiography, and for this purpose flatness of image field becomes rather more than a convention. It is fairly easy to design a system of lenses in contact, well corrected for spherical aberration and coma and giving an angle of convergence in the medium of the last one corresponding, for example, to a relative aperture of f/0.7; such a system will have uncorrected astigmatism and field curvature. If now the light emerge from the medium of the last lens of this aplanatic system through a surface which is in the aplanatic condition for axial imagery, and pass into a final lens of the same refractive index whose front surface is centred on the axial image and whose rear surface is plane and in the vicinity of the focal plane, this combination of three surfaces will introduce no further spherical aberration or coma, both of which are already corrected, will give a final aperture angle the same as that in the last lens of the aplanatic train, and will contribute astigmatism and field curvature which depend only on the positions of the two curved surfaces and may be made to balance the corresponding aberrations of the front aplanatic system. In practice it is found desirable to depart slightly from the exact fulfilment of these conditions to minimise high order comas, and good correction is attainable over a field of about 20°, with residual astigmatic errors from the ideal image surface of the same order as those given by Mr. Warmisham for his system. A typical lens is illustrated in Figure 2.

REFERENCES

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[2] British Patent Application No. 17753/'50, Wynne, C. G.
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REFLECTING MICROSCOPES

4. Practical Requirements in a Reflecting Microscope

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IN this communication I shall attempt to review some of the applications of reflecting microscopes and to stress the particular features of the objectives which render them specially suitable for such work. It has already become apparent, that it is not always necessary to have an " ideal " or " universal " type of reflecting microscope in order to cope with many problems in microscopy. Indeed in some cases this would be like using a sledge hammer to crack a nut. Within the last few years a number of simplified reflecting or reflecting-refracting objectives have been designed, which though of limited performance in some respects, are adequate for special purposes and are immeasurably easier to construct than the " universal " type. There seems little doubt that future progress will largely proceed in the direction of specialization of design for particular applications and it is therefore essential that designers should be quite clear as to the special requirements demanded of an objective for any individual purpose. Before considering these requirements in detail we must have some sort of standard by which the performance of an objective may be judged. The perfect reflecting objective does not exist but a good practical approach has been made in the Burch microscope [1] [2] either in its present form or in the improved form envisaged by Dr. Burch and his colleagues. The ideal reflecting objective (one might even omit the word " reflecting ") should have the following features :—

(1) Its N.A. should be as high as possible.
(2) It should be completely achromatic.
(3) It should be as free as possible from aberrations such as spherical aberration and coma.

(4) It should have as low an obstruction ratio as possible.
(5) It should have a long working-distance.

It may be useful to examine how far these requirements can be met in a practical instrument. The upper limit of N.A. is set by geometrical considerations. In a " dry " objective it cannot exceed 1·0 in theory and 0·95 would be a more practical value. The present Burch microscope has a " dry " N.A. of 0·65, and the proposed new microscope an N.A. of 0·95. In order to exceed these figures it is necessary to employ some form of refracting material as an immersion component. The N.A. will then depend on the refractive index of this material. In general the choice of lens material and immersion medium limit the N.A. to perhaps 1·4, though this value may be exceeded for special purposes (*e.g.* in metallography).

Complete achromatism is only obtainable in a purely reflecting system and in such a system the range of wavelengths which can be employed is limited only by the specular reflectivity of the mirrors. At the moment aluminized mirrors afford the best practical solution for work in most of the ultra-violet, visible, and infrared regions of the spectrum. The reflectivity of nearly all metallic surfaces is high in the infrared region and the problem is not a serious one. Much the same can be said of the visible region but the ultraviolet is rather more difficult. The experimental work on the reflectivity of metallic surfaces produced by modern methods is not as complete as could be wished, and new measurements in the ultraviolet region are badly needed. Aluminium has a fairly high reflectivity down to at least 2000 A.U. but like most other metals the reflectivity falls off gradually below 4000 A.U. A reduction in reflectivity from say 90% to 85% may not at first sight seem important, but it must be remembered that at least four (and frequently more) reflecting surfaces are involved, so that the cumulative effect may be considerable. The varying loss of intensity with wavelength may be particularly objectionable in microspectrographic applications. The use of immersion components for increasing N.A. of a reflecting objective may affect the chromatic corrections and the range of utilizable wavelengths. In the Burch microscope the immersion component is a spherical lens with its centre of curvature at the object point. The result of this is that whereas the longitudinal achromatism is unaffected, chromatic difference of magnification is introduced. This latter effect is rarely obtrusive and can be corrected if desired. As an alternative to the normal-incidence immersion component, it is possible to use an Amici lens component. This has the advantage that it confers a high N.A., but at the price of achromatism. Nevertheless if a suitably calibrated mechanism for moving the Amici component be provided, the objective could be used as a " monochromat " over a wide spectral range. The use of immersion components introduces problems concerning the choice of suitable immersion medium. The latter should match the lens material in both refractive index and dispersive power if aberrations are to be avoided. The spectral absorption of both lens material and immersion medium must also be taken into consideration. Fortunately there is a reasonably good choice so far as the visible and ultraviolet regions are concerned as silica, fluorite, and synthetic lithium and calcium fluoride are all sufficiently transparent for use over the biologically important region (above 2200 A.U.). Water, glycerine, or mixtures of the two, glucose solutions, and cyclohexane can be used as immersion media. It is of course essential for ultraviolet work that both lens medium and immersion medium should be free from fluorescence. The choice of materials for infrared work is less satisfactory. Quartz (3μ), lithium fluoride (6μ), calcium fluoride (9μ), rocksalt (15μ), potassium bromide (25μ) and thallium bromoiodide (50μ) are the main substances available for making lenses, the figures in brackets indicating the upper limits of transmission. Most of the alkali halides tend to be soft and hygroscopic. The selection of an immersion medium for infrared work above 3μ is extremely limited as all liquids show absorption bands in some regions of the infrared spectrum, and it is necessary to select a liquid whose absorption bands clash as little as possible with those of the specimen. Liquid paraffin (Nujol) would probably be a suitable compromise in the majority of cases.

A final limitation to the achromatism of a microscope must be mentioned, namely that due to the presence of the supporting slide and coverslip. The effects of these can be reduced by making them as thin as possible. For some purposes I have used very thin collodion membranes, similar to those used in electron microscopy, as slide and coverslip, and the chromatic disturbance introduced by such membranes is negligible. To summarize the question of achromatism, we see that in practice there is no such thing as a *completely* achromatic microscope. In the final analysis there is always the disturbing effect of the specimen itself and the slide on which it is mounted. With certain precautions however, the purely reflecting objective can be as nearly achromatic as desired, and the spectral range is limited only by the reflectivity of the mirrors. The introduction of lens components always affects the achromatism to some extent and limits the spectral range.

Let us now consider the problem of other aberrations. It can be said at once that the standard required in a reflecting objective should not be less than we are prepared to accept in a refracting objective. Unfortunately there are no very satisfactory rules to guide us. The Rayleigh Criterion has usually been regarded as a standard of perfection but there have been suggestions that it may be too rigorous in practice. This may be so, but on general grounds any lowering of accepted standards is to be deprecated. It must of course be remembered that tolerances should be calculated in terms of the shortest wavelengths for which the instrument is likely to be used. It follows that for a " universal " microscope sufficiently good for use in the ultraviolet region the visual performance should be superlatively good. There is one aberration, namely coma, which it is of particular importance to eliminate as far as possible in reflecting objectives. This is because one of their most important applications is to microspectrophotometric work and for this it is essential, as has been stressed by Caspersson,[3] that the objective should obey the sine condition. If this is not the case it is difficult to make any accurate measurements on the spectral absorption of a microscopic object.

Some of the problems of aberrations in reflecting microscopes of the Schwarzschild type have been considered by Burch[1 2]. Briefly, his conclusions were that in order to construct an aplanatic objective of N.A. greater than 0·5 it is necessary to make at least one mirror aspherical. If the N.A. is to exceed 0·65 it is generally necessary to make both mirrors aspherical. Both mirrors can be spherical if the N.A. does not exceed 0·5. These conclusions refer to a purely reflecting objective without any correcting lens components. It will be apparent therefore that our " ideal " purely reflecting objective will be one in which both mirrors are aspherical. It is the considerable practical difficulty involved in the construction of such mirrors which had led designers to seek for simple solutions which avoid aspherical surfaces.

The use of aspherical mirrors confers another important advantage on a reflecting objective, in that it allows the obstruction ratio to be reduced. This is a matter of such great practical importance that it deserves further consideration. In all reflecting microscopes part of the objective aperture is stopped out either due to the shadow of a secondary mirror or because of the way in which the object has to be mounted. This obstruction ratio may be quite considerable in some designs—even exceeding 50% of the numerical aperture (25% of the exit pupil area). One effect of this is a loss of light which is not usually serious. Far more serious is an alteration of the Airy Disc pattern resulting in a decrease of intensity in the central disc accompanied by an increase in the outer rings. The practical results of this change are not immediately obvious as they depend on the type of object under observation. In general however some loss of contrast is to be expected, and if the object already possesses low contrast its visibility may be seriously reduced and microspectrophotometric measurements rendered inaccurate. It is therefore very important to know what is the maximum obstruction ration which can be tolerated in a practical instrument. Some figures bearing on this are shown in Table I. The criteria of Bouwers [4] and Grey [5] are suggested upper limits based on both practical and theoretical considerations. The other figures refer to commercial and experimental designs described in the literature. It will be seen that the two Burch microscopes (in which aspherical mirrors are used) have obstruction ratios well below the limits set by Bouwers and Grey. The other objectives so far described generally exceed these limits by varying amounts. There is very little published work to help the practical microscopist to decide exactly at what point the obstruction ratio becomes excessive. It was therefore decided to

TABLE I.

Characteristics of Reflecting Objectives.

	Obstruction ratio		N.A.	Working Distance
	% N.A. (radius)	% Area		
Bouwers' Criterion ...	30	9	—	—
Grey's Criterion ...	32	10	—	—
Concentric pair ...	45	20	0·5	—
Burch (Oxford) ...	14	2	0·65 (0·98 with immersion component)	13 mm.
Burch (London) ...	25	6	0·58	—
Bausch & Lomb (Grey)	30	9	0·72	0·8 mm.
Beck (*a*)	35	12·5	0·65	4·75 mm.
Beck (*b*)	42	17·5	0·65	4·75 mm.
American Optical Co....	50	25	0·56	3·8 mm.

investigate this question in a simple way. Two similar " achromatic " lens objectives, each of N.A. 0·65 were chosen and set up on two separate microscopes with illumination and objects as nearly as possible identical. A series of stops was introduced behind one objective and the quality of the image compared with that produced by the other objective. The results were of course purely subjective and no great quantitative significance can be attached to them. More exact photometric determinations on standard objects would be highly desirable. It was found that with most stained biological sections no significant effect could be observed with obstruction ratios less than about 5% of area. Between 5% and 10% there was a progressive reduction in contrast, which seemed to fall off with even greater rapidity above 10%. Thus the loss of contrast in changing from 10% to 13% obstruction was much more obvious than in the change from 7% to 10%. These observations are thus in essential agreement with the criteria of Bouwers and Grey. Experiments of this type and the examination of a number of experimental and commercial reflecting objectives lead me to suggest certain tests which are useful in trying out a reflecting objective.

(1) Always try to compare the image of a familiar object with that seen by means of a standard lens objective of equivalent N.A., using similar conditions of illumination.

(2) Beware of judging the merits of an objective solely by its performance with test diatoms. I have repeatedly found that objectives with high obstruction ratios may resolve diatoms with quite good contrast but fail miserably with other types of object.

(3) One of the most useful types of object is an ordinary biological tissue section stained, for example, with haematoxylin and eosin. A stained blood film is particularly valuable. If an objective does not perform reasonably well with such objects it is not likely to be of much use for biological purposes.

(4) Examine the boundary of a heavily absorbing object, such as the edge of a razor or the rulings of an Abbe test plate. With high obstruction ratios the edges are often not sharply black-and-white but grey-and-white.

(5) Examine the pinholes in a metallized slide (star test). The first diffraction ring may be unduly bright. This test object should also be used in the usual way for the detection of spherical aberration and coma. These suggestions are not exhaustive and many other tests can be applied. The Golden Rule to remember, however, is

if the objective does not perform well in the visible region it is not very likely to perform well in the ultraviolet, with comparable types of object. It is astonishing to observe how often this almost self-evident rule is ignored or forgotten.

A useful, though in some respects fortuitous property of most reflecting objectives is that they usually have a working distance considerably greater than that of equivalent refracting objectives. Thus the Burch microscope at Oxford has a working distance of approximately 13 mm. at N.A. 0·65. The working distance can be altered by changing the scale of the objective so that in principle at least, there is no upper limit. The scaling up of a lens objective in order to increase the working distance is not so simple, as this process also increases residual aberrations. The question of the most desirable value for the working distance will be discussed below.

Having discussed some of the factors which may limit the performance of even an "ideal" reflecting objective we may now consider the features which would be specially desirable for any particular purpose. In general the applications to which a reflecting objective can be put can be considered under the heading of (1) Achromatism, (2) Long working-distance, though for many purposes the simultaneous presence of both is an advantage.

The applications for which the achromatic properties must be specially considered are U.V., visible and infrared microscopy and microspectrophotometry.

Ultraviolet Microscopy and Microspectrophotometry

The range of wavelengths most frequently used for biological U.V. microscopy extends from 2500 A.U. to 3000 A.U. The wavelengths for which quartz refracting objectives are usually corrected are either 2537 A.U. (Mercury) or 2750 A.U. (Cadmium). These latter objectives require to be illuminated by monochromatic light but with an achromatic objective a wider band can be used, thus reducing exposure time. An objective chromatically corrected over a band of say, at least 100 A.U. could be used in conjunction with narrow-band U.V. filters, thus avoiding many of the difficulties associated with the use of monochromators. A valuable, in fact almost essential feature in a ultraviolet microscope is the ability to focus with visible light without the necessity of altering focus for U.V. photography. This necessitates either achromatism extending over the U.V. and visible ranges or an objective which is " polychromatic," *i.e.* in focus simultaneously at two or more separate wavelengths. Such an objective has been described by Johnson.[6] The requirements for U.V. microspectrophotometry depend on the type of technique to be adopted. If measurements are to be made separately at a number of wavelengths, using monochromatic light [3] [7] a high degree of achromatism is not essential, though it will facilitate focusing. Constancy of other aberrations over the spectral range studied is however highly desirable. If on the other hand a wide spectral band or a number of different wavelengths are to be observed simultaneously by using the microscope in conjunction with a spectrograph,[8] [9] then very good achromatism is required, as well as constancy of other aberrations. This method requires that an image of the microscopic object should be projected onto the entrance slit of the spectrograph. It is often better not to use an eyepiece, which may introduce aberrations or restrict the spectral range, but to project the primary image. The magnification is then governed by the projection distance. If the latter needs to be varied considerably from the mechanical tube length, spherical aberration will be introduced. Some method of correcting this must be provided. In the Burch microscope this is effected by altering the distance between the two mirrors. The same control enables the user to overcome the effects of variation in cover slip thickness and is therefore extremely valuable, even though it complicates the mechanical design. From what has already been said it will be clear that the reduction of the obstruction ratio is of great importance in ultraviolet microscopy and microspectrophotometry. Photographic contrast is low in the U.V. and it is therefore essential that other causes of loss of contrast should be eliminated as far as possible.

An outstanding example of an objective sufficiently achromatic to be used in the range 2200 A.U. to 6000 A.U. has been provided by the work of D. S. Grey.[5] His objectives contain both reflecting and refracting elements, and only spherical surfaces are used. Excellent correction of aberrations, comparatively low obstruction ratio and high N.A. can be attained. The main disadvantages are a certain complexity of construction, difficulty of centration, the use of both fused quartz and fluorite lens components and rather a large number of air-lens interfaces. Despite these, Grey's work represents the achievement of an aim which only a few years ago would have been regarded as unattainable, and further progress may be expected along these lines.

Another approach to the problem has been made at King's College, London. It was shown by Burch[1] that it is possible to design a Schwarzschild objective of N.A. approximately 0·5, with excellent corrections and using only spherical mirrors provided that these mirrors were concentric. Unfortunately, such objectives have the prohibitively high obstruction ratio of 45% of N.A. By deviating from the roughly concentric condition, changing the relative dimensions of the mirrors, and controlling their separation by means of a microscope-testing interferometer, it has been possible to increase the N.A. and at the same time reduce the obstruction ratio.[10] The characteristics of two such objectives, constructed by Messrs. R. & J. Beck are shown in Table I. I understand that even smaller obstruction ratios have been achieved. Unfortunately it would appear likely on theoretical grounds that this must result in some increase in coma, unless the field is to be made very small. The great importance of avoiding coma in objectives used for microspectrophotometry has already been stressed. A full practical evaluation of these objectives is awaited with interest.

Microscopy and Microspectrophotometry in the Visible Region

Modern achromats and apochromats give such a good performance that it may be questioned whether any advantage is to be expected from the use of reflecting objectives. In order to compete with the best lens objectives a reflecting objective should have at least as good a performance so far as spherical aberration and coma are concerned, and a considerably better chromatic correction. Other factors to be considered are simplicity of construction, cost, and working distance. Unfortunately the key to the problem is once again the obstruction ratio, and as the price requirements preclude the use of aspherical mirrors, there seems little prospect of making a first class objective without lens components. The objectives designed by Bouwers[4] employ plane and spherical mirrors with correction lenses. The N.A. of these objectives are 0·2 and 0·4 and for these values the obstruction ratios can be kept within reasonable limits. Other designs of higher N.A. and using immersion components have also been completed.

In this country a " solid " objective has been designed by C. G. Wynne. Here both mirrors are metallized surfaces on a solid block of glass. The first objective of this type gave poor contrast due to the high obstruction ratio but an improved objective with correction lenses and a reduced obstruction ratio is now in course of construction. Such objectives may be extremely important in the future as the mirrors are permanently mounted and all risk of damage and decentering is avoided. The chromatic corrections are better than those of an apochromatic lens, and the working distance for an objective small enough to fit onto a standard microscope is considerably greater. A successful design of this type may well become the routine research objective of the future. Rather similar solid objectives have been proposed by Drew,[11] but these incorporate aspherical surfaces. The possibility that " solid " objectives may be made of materials transparent to other regions of the spectrum should not be overlooked.

Infrared Microscopy and Microspectrophotometry

Infrared microscopy, using either photographic or photoelectric image-converter techniques [12] is usually restricted to wavelengths below $1{\cdot}5\mu$. In the present state of the subject it is very doubtful whether objectives specially constructed for this purpose are needed. Most reflecting and semi-reflecting objectives could be used in the near infrared. The ability to focus in the visible region is of value in infrared photomicrography, but becomes unnecessary if image-converters are used. The situation is very different in infrared microspectrophotometry.[13] Here the wavelength range required extends to at least 14μ though useful work could sometimes be carried out with narrower bands, *e.g.* up to 5μ. A purely reflecting system is undoubtedly the best solution when an extensive wavelength range is required. The resolution is greatly reduced at long wavelengths and therefore if it is desired to work with small objects the N.A. should be as high as possible. Difficulties encountered in using immersion components in the infrared have already been pointed out. A more fortunate consequence of the use of long wavelengths is that the accuracy of construction need not be so great. Thus if the minimum wavelength to be used is about 3μ, the Rayleigh Criterion corresponds to about 1½ wavelengths of visible light. The possibility of making aspherical surfaces to this degree of accuracy by moulding should be investigated. The avoidance of coma and high obstruction ratio is just as important in the infrared as elsewhere, for even though no actual image is seen, the sharpness and depth of absorption bands may be adversely affected.

The use of polarised light with reflecting objectives

One of the most useful applications of the Burch microscope has been to the detection of dichroism in the ultraviolet and infra-red regions, by observing the change in absorption spectrum as the direction of polarization of incident radiation is varied. It might be expected that a certain amount of depolarization might occur in a reflecting system. It is true that the extinction between crossed polarizers is not as perfect as can be obtained with a good lens objective (due probably to elliptical polarization at the metallized mirror surfaces) but it is adequate for qualitative work. The obstruction ratio may also have some bearing on the use of polarized light. For most polarization work it is usually best to use narrow illuminating cones so that the path length of rays passing through the object should not vary too much. The effect of the central obstruction is to block out just those narrow angle rays. This may be important when measurements of weakly dichroic bands are involved.

Long working distance

This property is always useful, and in some cases essential. Its main applications are in high and low temperature microscopy, micromanipulation, and the examination of thick objects such as nuclear track photographic emulsions. The exact value of the working distance required will depend on the particular application. Thus in high temperature microscopy it will depend on the temperature, whether a vacuum chamber is used, and whether special cooling precautions are provided. Obviously for maximum safety the working distance should be as large as possible. It is possible to specify the working distance more exactly when the objective is to be used for micromanipulation. A clearance of one centimetre between the object and the nearest point of the objective (or the objective mount) is usually quite adequate. In some cases it is possible to reduce this distance but it is rather doubtful whether micromanipulation could be conveniently carried out with working distances less than 5 mm. The geometrical form of the objective and its mount should also be considered. Thus the part of the objective nearest the object should be as narrow as possible and large bulges should be avoided so that plenty of space is allowed for introducing instruments at an angle. In some designs many of the advantages of the long working distance are lost because these factors have been ignored. A particularly successful solution to the problem of working distance has been presented by Dyson.[14] A combination of a plane and spherical mirror is used to form an image at unit magnification, and the latter is then examined by means of a standard lens objective. I have used two objectives based on this design. One has N.A. 0·2 with working distance 34 mm., the other N.A. 0·57 with working distance 11 mm. The optical performance in each case is quite satisfactory, and the objectives have been used for micromanipulation with phase contrast illumination, and for high temperature microscopy. An objective very similar to that of Dyson has been designed independently by Heal[15] in which the mirrors are mounted on a solid block of glass. The system has been used for high temperature microscopy of metals, using dark-ground illumination. It is clear that the development of such objectives, which are relatively cheap and simple to produce, is an outstanding advance and they will find widespread application wherever working distance, rather than achromatism, is of primary importance.

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NOTE ADDED IN PROOF

Since the above paper was written, I have been able to look into the question of the effect of the obstruction ratio in more detail. It appears likely that in the experiments carried out on two similar achromatic lens objectives at least part of the deterioration may be due to the relatively poor correction of the outer zones of the lenses. On examining a very well corrected concentric mirror reflecting objective, I was surprised to observe how good the contrast appeared to be, even though the obstruction ratio was very high. The effect of aberrations and obstruction ratio may therefore be additive, and Mr. D. S. Grey has recently informed me that theoretical work shows that this is in fact the case within certain limits. A full theoretical and practical investigation of the effect of obstruction ratio is being carried out by Dr. T. Dunham (see Special Report No. 2, American Cancer Society Grant No. PH 1B 1948, Mass. Institute of Technology).

SOMMAIRE **SUMMARY**

Les charactéristiques interessantes des objectifs catadioptriques sont l'achromatisme et la grande distance frontale. Le fait qu'elles sont associées est fortuit mais hereux.

1. *Achromatisme.* Il n'est pas toujours parfait ; seul un système purement catoptrique est parfaitement achromatique et la bande de longeurs d'ondes dans laquelle il peut être utilisée n'est limitée que par le pouvoir reflecteur des miroirs. Des systèmes catadioptriques peuvent être suffisamment achromatiques pour être utilisables dans des régions spectrales limitées, mais l'absorption des radiations par les éléments refringents limite sérieusement leur utilisation.

Dans les systèmes destinés à l'U.V. ou a l'I.R. il est essential de pouvoir mettre au point dans le visible. Si l'on veut effectuer une photomicrographie rapide un système polychromatique peut suffire.

Pour l'étude de l'absorption spectrale des objets microscopiques (' spectromicrographie ') il est utile d'obtenir un bon achromatisme pour pouvoir enregistrer de façon continue les spectres pour toute longeur d'onde. Le microscope de Burch a été utilisé depuis 240 mμ dans l'U.V. jusqu'a 14 μ dans l'I.R. et il est peu probable qu'un tel intervalle spectral puisse être étudié à l'aide d'un seul objectif catadioptrique. Pour le travail biologique l'ouverture numérique doit être aussi élevée que possible et une valeur minimum de 0·5 est proposée. Le rapport d'obturation centrale doit être inférieure a 30% si l'on veut éviter une sérieuse perte de contraste dans l'image.

2. *Grande distance frontale.* Les principales applications de cette propriété sont la microscopie à basse ou haute température, la micromanipulation, et l'examen d'objets épais. L'achromatisme n'est pas indispensable dans ces applications et le plus souvent on se serve à utiliser la lumière visible. Il serait trés souhaitable de construire des systèmes catadioptriques à grande distance frontale. Un système de ce genre, dû a Dyson, utilise un objectif dioptrique ordinaire. Un objectif d'ouverture numérique 0·57 et de distance frontale 11 mm. a été construit. En général, une distance minimum d'environ 1 cm. serait utile.

Il n'est par sûr que l'on puisse utiliser la micromanipulation avec une distance frontale inférieure a 5 mm.

The distinctive features of reflecting objectives can be discussed under the headings of: (1) Achromatism; (2) Long working-distance. The fact that these properties are associated is fortuitous but fortunate.

(1) *Achromatism.* This is a relative term. Only a purely reflecting system is truly achromatic, and the range of wavelengths over which it can be used is limited only by the reflectivity of the mirrors. Reflecting-refracting systems can be made sufficiently achromatic for use over limited spectral regions, but absorption of radiation by the refracting elements is an important limiting factor.

In any system to be used in the ultra-violet or infra-red it is essential to be able to focus in the visible. If only straightforward photomicrography is required a polychromatic system may suffice. For absorption spectroscopy of microscopic objects (spectromicrography) the highest possible degree of achromatism is desirable in order to record spectra continuously at every wavelength. The Burch microscope has been used over a range extending from 240 mμ in the ultraviolet up to 14μ in the infrared, and it is unlikely that such a range could be covered by any single reflecting-refracting objective. For biological work the N.A. should be as high as possible, and a minimum value of 0.5 is suggested. The obstruction ratio must be kept below 30% of aperture if a serious loss of image contrast is to be avoided.

(2) *Long working-distance.* The main applications of this property are high and low temperature microscopy, micro-manipulation, and the examination of thick objects. Achromatism is not often of primary importance in these applications, and in most cases only visible light is used. The development of simple reflecting-refracting systems with long working-distance is highly desirable. One such device, due to Dyson, uses a reflecting system to form an image at unit magnification, which is then examined by means of a conventional lens objective. An objective with N.A. 0.57 and working distance 11 mm. has been constructed. In general a minimum working distance of the order of one centimeter is desirable. It is doubtful whether micromanipulation could be performed with working distances less than 5 mm.

5. Reflecting Microscopes

A. BOUWERS
(De Oude Delft, Netherlands)

During the last ten years considerable success has been obtained by reflecting objectives for microscopes.

Several authors, among which are Linfoot[1], Bouwers[2], Johnson[3], Burch[4], Brumberg [5], Grey and Lee[6], have worked in this new field and arrived at various constructions, which can be divided in two types :

I. catadioptric objectives in which the aberrations of one or two mirrors are corrected by one or more lenses ;
II. objectives consisting of two mirrors, without lenses.

As an example of the application of the first type a complete reflecting microscope with a catadioptric objective with N.A. 0·20 according to one of us[2] is demonstrated. A detailed description thereof has been given by Bouwers[2] and Hekker[7]. Recently a new version of the same type with N.A. 0·40 has been developed.

Burch[4] has designed and made objectives of the second type, one of the mirrors being aspherically surfaced.

The new objective which will be described hereinafter belongs to the second type, but has spherical surfaces only.

An All-glass Two Mirror Objective

It is known that any degree of spherical undercorrection can be obtained with a single concave spherical mirror by varying the magnification.

The same applies to the spherical overcorrection of a spherical convex mirror. It appears that a combination of a concave and a convex spherical mirror with N.A. 0·60 can be obtained in which both the marginal rays and the rays in the zone are corrected for spherical aberration within the Rayleigh limit.

A very interesting version has been realised by putting both mirrors in a medium of glass or any other transparent medium. The advantages obtained in this all-glass type are :

1. small obstruction ratio
2. considerably greater N.A.

In Fig. 5.1 an example of this objective is given.

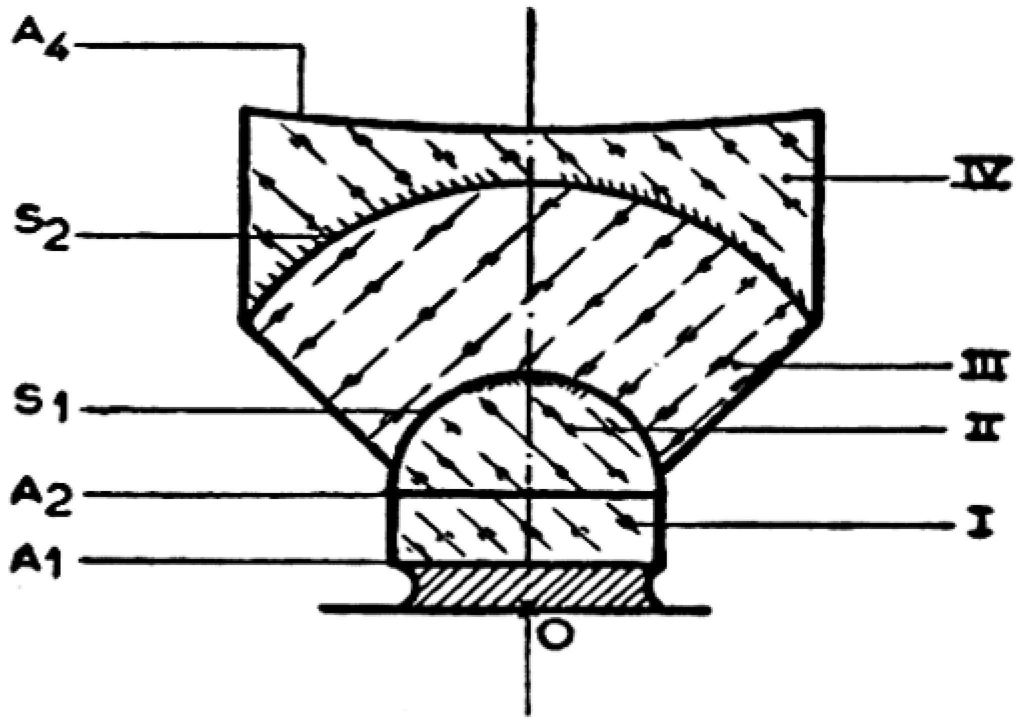

FIG. 5.1. An all-glass two-mirror objective.

The system consists of four components all made of the same glass. The part I nearest the object and in contact with the immersion liquid is a plane parallel plate.

Part II is a hemisphere with centre of curvature in the interface A_2 in which a stop is placed.

The concave surface of part III is partly aluminised (mirror S_1) in a manner to be described hereinafter and the convex surface of III is aluminised except for the central portion (mirror S_2). Part IV has two concave surfaces, the outer one having its centre of curvature in the axial point of the image. The thickness of the plate I can be chosen at will. By making it small the working distance is increased. The latter is practically equal to the focal distance if I is omitted. This feature of great working distance can be of great importance for some kinds of microscopical work e.g. the inspection of nuclear tracks in thick photographic emulsions. The two mirrors S_1 and S_2 are spherical and concentric ; as a stop is placed at the centre of curvature there is no coma and no astigmatism. The immersion being homogeneous the light rays are not refracted at the oil-glass interface. As a consequence of the different dispersions of the oil and the glass there is only a slight longitudinal chromatic aberration, which however is too small to be detected. The reflections at S_1 and S_2 are the same for all wavelengths. The rays emerging from the objective traverse the surface A_4 perpendicularly. Hence the image is free from chromatic aberration for a point at the centre of the field of view. There is some small lateral chromatic aberration due to surfaces A_1 and A_4. However, the chromatic aberrations of these surfaces are opposite in sign. In testing the prototype, no chromatic aberration has been found.

The obstruction ratio of this objective could be reduced by the following procedure. The central disc with radius CP_2 of S_2 is opaquely aluminised (Fig. 5.2). Then a ring P_1P_2 is half aluminised while the outer section beyond P_1 is not aluminised at all. By correctly choosing the size of ring P_1P_2 the light intensity of all rays emerging from the centre O of the object can be reduced in the same ratio. To that effect the points P_1 and P_2 are chosen as follows. Trace a ray $O\ Q_1$, with the maximum aperture of the objective. This ray is reflected at the mirror S_1 as Q_1P_1, where P_1 is the intersection with the surface S_2. Now the ray OP_1 intersects the mirror S_1 in Q_2 and is reflected as Q_2P_2. If the concave surface is aluminised as indicated above, the rays with great aperture pass S_2 with no losses, are reflected first at the fully aluminised mirror S_1 and then partially at the ring P_1P_2 on S_2 and emerge finally through the non-aluminised central portion in S_1. The light intensity of the rays of smaller aperture is reduced by the ring P_1P_2 of S_2. These rays are reflected at S_1 and then by the fully mirrored central disc of S_2. The phase difference between the two groups of rays introduced by this device is very small.

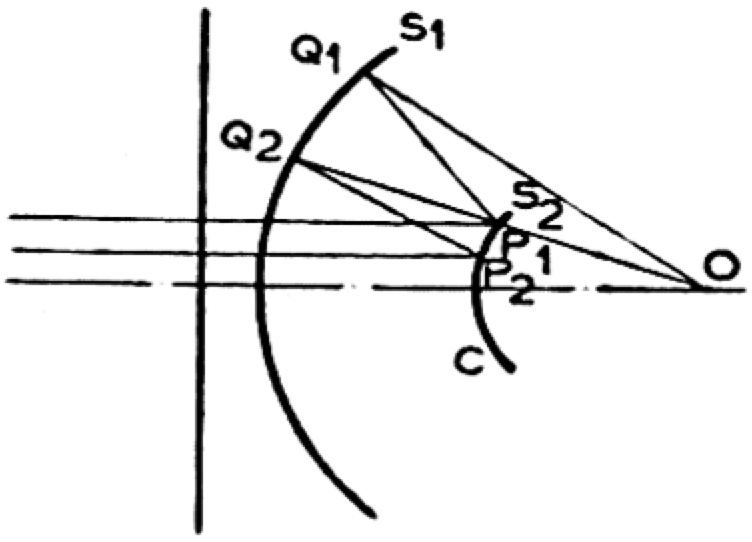

FIG. 5.2. Method of reducing obstruction ratio of the objective.

The first group of rays is thus reduced in intensity by partial reflection at P_1P_2 whereas the second group is reduced in intensity by transmission in the same zone. In order to reduce both groups to the same amount the reflection has to be equal to the transmission. This is the case if both are equal to about 1/3, the absorption being about 1/3. The amount of light in microscopical images being mostly abundant this is no serious limitation. By this procedure the obstruction ratio is reduced to only 20% in diameter or 4% in area.

One version made in August 1949 has a focal distance of 1·98 mm., a numerical aperture of 0·92 and a magnification of 93×.

With this objective some photographs have been taken of tracks of elementary particles in a photographic plate. A reproduction of a 510 times enlarged image of a proton track shows that the definition of the grains at the border of the image is as good as in the centre, due to the concentricity of the system.

This objective has been made of boro-silicate crown and can be used in visible light and in the near infrared region. By applying quartz or other materials which are transparent in the ultraviolet and infrared regions the objective can be used for all wavelengths.

The cementing must be carried out with a substance transmitting in the U.V. and I.R. region. The same applies to the immersion liquid.

As the difference in refractive index between the liquid and the quartz glass is not very small in this case the plane surface A_1 may be replaced by a curved one, concave towards the object. If the centre of curvature is coincident with the object, this objective can be used too without immersion.

Two further examples are represented in Fig. 5.3 and Fig. 5.4. The objective of Fig. 5.3 has a focal length of 0·9 mm. and N.A. 1·25. Due to the additional aplanatic lens the quality of the image towards the border of the field is not as good as with the purely concentric system.

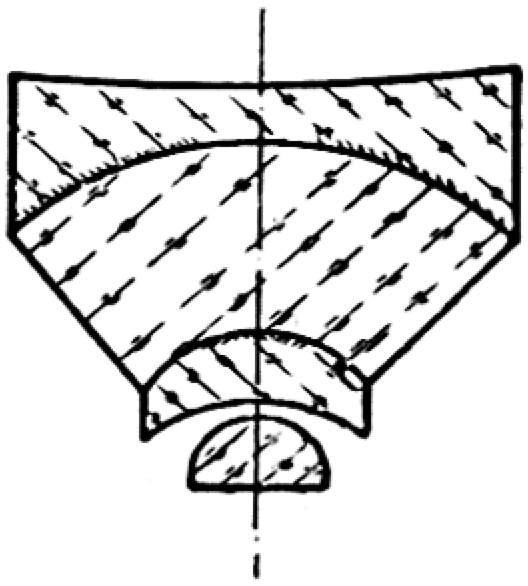

FIG. 5.3. Example of two-mirror objective with N.A. 1.25 and f/0.9.

The version of Fig. 5.4 has a focal length of 0·88 mm. and N.A. 1·10.

Surface 1 is concentric with the axial point O of the object. The plane surface 2 is half aluminised and the concave mirror 3 is opaquely aluminised with the exception of a small central portion at O_1.

This objective has a N.A. of 1·10, the image quality being very good up to the very border of the field. The wave front deviation is kept well within the Rayleigh limit.

Further work in progress indicates that slight alterations of the designs so far mentioned will lead to an increase of numerical aperture to about 1·3.

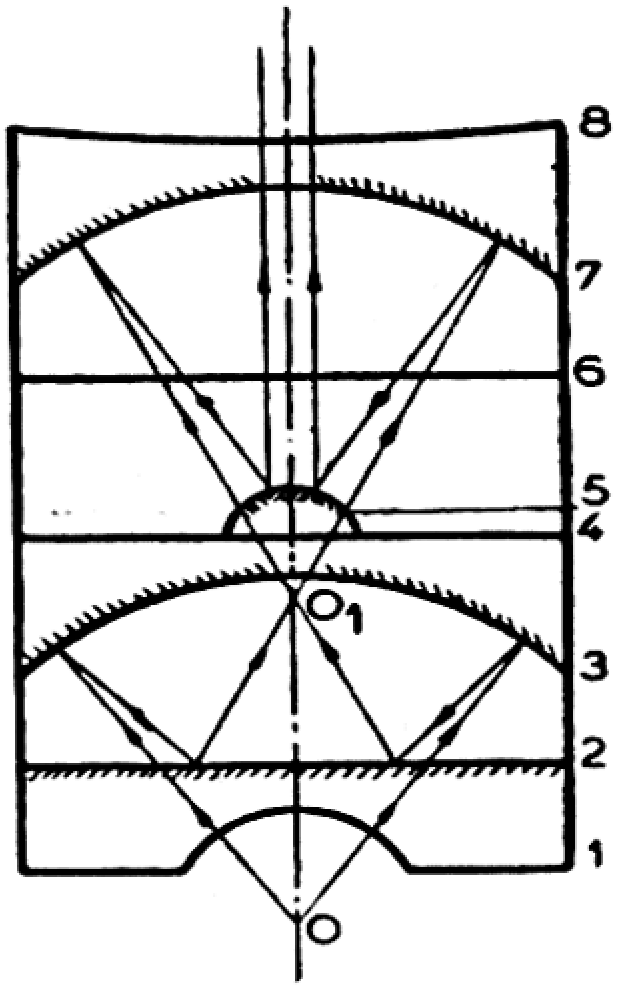

FIG. 5.4. Two-mirror objective with N.A. 1.1 and f/0.88.

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SOMMAIRE

SUMMARY

Les microscopes à réflexion comportant essentiallement des systèmes de miroirs concentriques ont déjà été décrits en detail.* Deux microscopes différents ayant des ouvertures numériques égales a 0·2 et 0·4, équipés pour projection d'objets transparents ou opaques sont fabriqués depuis un certain temps. La réalisation la plus récente est présentée.

La présente communication traite de l'évolution des objectifs à miroirs concentriques. Trois objectifs récents sont décrits :

(a) un objectif concentrique d'O.N. 0·6.

(b) un objectif d'O.N. 0·9 à immersion à huile et avec une distance frontale exceptionallement grande.

(c) un objectif à immersion d'O.N. 1·3.

Le dernier, qui subit encore des modifications, a été conçu selon les mêmes principes que les objectifs (a) et (b).

Reflecting microscopes based on essentially concentric mirror systems have already been described in some detail.* Two different microscopes with fixed numerical aperture 0.2 and 0.4, fitted with projection equipment both for transparant and opaque objects, have been available for some time. The newest version will be demonstrated.

The present paper deals with the further development of concentric mirror objectives. Three recent objectives are described :—

(*a*) a concentric objective with N.A. 0.6 ;

(*b*) an objective with N.A. 0.9 with oil immersion and unusually large working distance ;

(*c*) an immersion objective with N.A. 1.3.

The last, which is still in course of development, has been designed along the same lines as the objectives (*a*) and (*b*).

* "Achievements in Optics."

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6. A Family of Catadioptric Microscope Objectives

DAVID S. GREY
(The Polaroid Corporation, U.S.A.)

Biologists are no longer content to study only structural outlines. They are becoming interested in classifying the constituents which *form* the fine detailed structure observed. Preferably, this classification would present a model of cellular structure in terms of chemical composition. If we accept this problem, we must realize that it probably cannot be *completely* solved. We must utilize all research techniques which present relevant information, refine each to its theoretical limits, and finally base our conclusions and assess our uncertainty in the light of all obtainable and pertinent data. Our several methods of microscopy are probably the most powerful tools available for this study. The absorption spectra of microscopic areas can reveal valuable information about the chemical composition of fine structure. The design and construction of reflecting microscopes and of catadioptric microscopes in the United States of America has been undertaken for this specific purpose.

Professor John R. Loofbourow at the Massachusetts Institute of Technology and the Research Group at the Polaroid Corporation became interested in pursuing the ultraviolet absorption studies initiated by T. Caspersson at the Karolinska Institute. It seemed apparent that an ultraviolet microscope which may be freely used as a research tool requires an objective which brings to a common focus all the ultraviolet wavelengths of particular interest—say about 220 to 320mμ. Apparently the only method of achieving such correction at large or even at intermediate numerical aperture is to use reflecting systems or catadioptric systems.

The Schwarzschild Mirrors

There are two basically different types of mirror combinations which may form the basis of a microscope design (Fig. 6.1). These may be called the generalized Newtonian and Schwarzschild systems, respectively. The Schwarzschild-type microscope objective had been described in the literature by C. R. Burch and Brumberg, and a modern adaptation of the Newtonian system by Bouwers and Maksutov. Mr. Kavanagh at the American Optical Company, and your speaker at Polaroid Corporation, independently studied the design of reflecting ultraviolet microscopes and both selected the Schwarzschild type with spherical mirrors. This choice was primarily based on the larger fraction of the central aperture which is occluded, or obscured, by the secondary mirror in the Newtonian system.

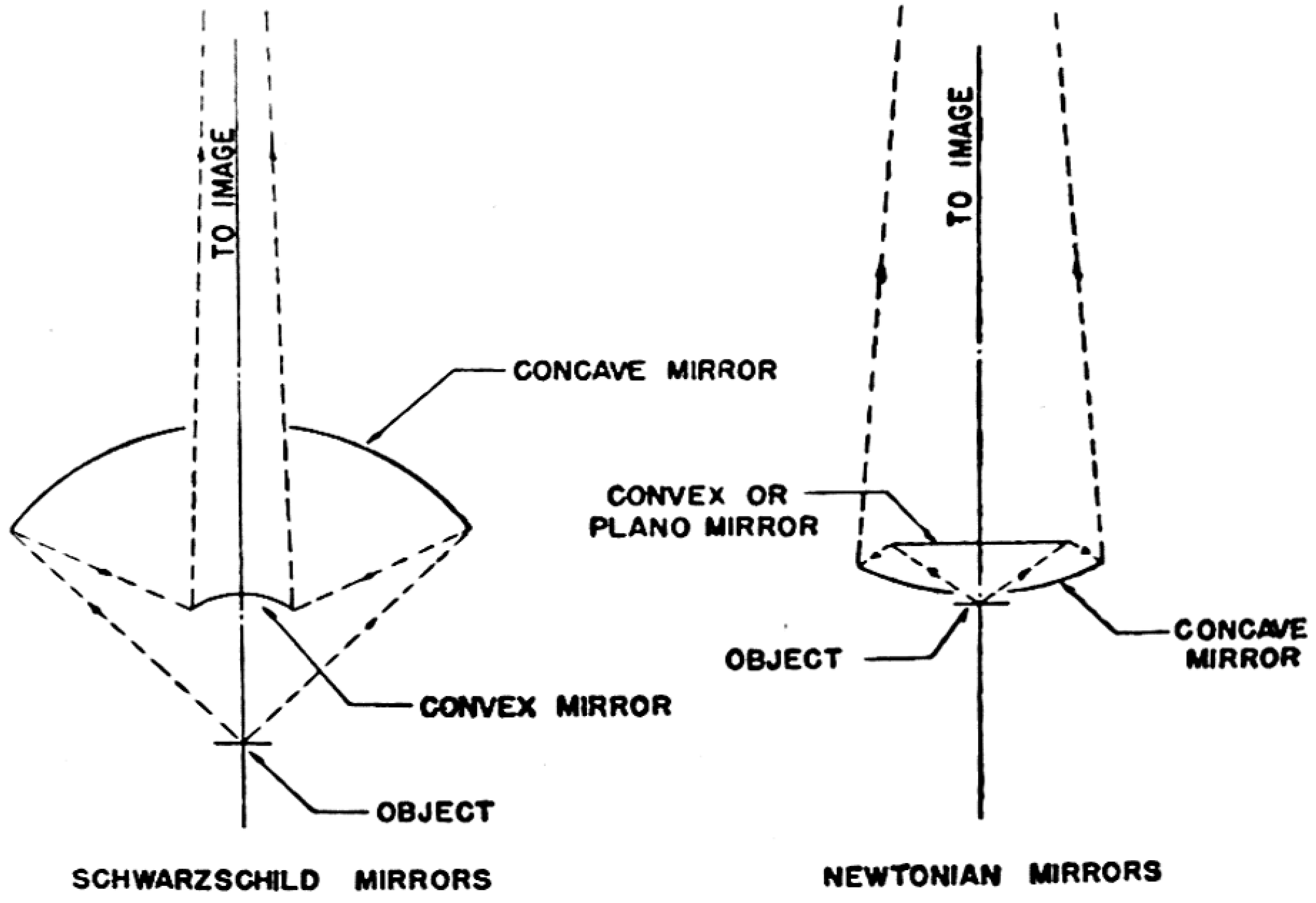

FIG. 6.1. Newtonian and Schwarzschild types of two-mirror objectives. In the Schwarzschild system (left) a convex mirror is optically located nearer to the long conjugate focus than is the primary (concave) mirror.

Schwarzschild objectives, which essentially contain only two spherical mirrors, may be corrected for ultraviolet use at numerical apertures up to about 0·55, and with the occluded portion of the aperture equal to about 20 per cent of the *area* of the exit pupil. Mechanical supports for the convex mirror necessarily add to the obscuration. Kavanagh at the American Optical Company has computed such systems with NA 0·56. By adding a hemisphere with centre of curvature approximately at the object point, Kavanagh realized NA 0·85 with immersion.

Lens Elements combined with the Schwarzschild Mirrors

My own investigation of modified Schwarzschild systems was guided by the desire to reduce the occluded fraction of aperture, but without using aspherical surfaces, and without sacrificing correction of chromatic aberrations for wavelengths from 220 mμ through the visible spectrum.

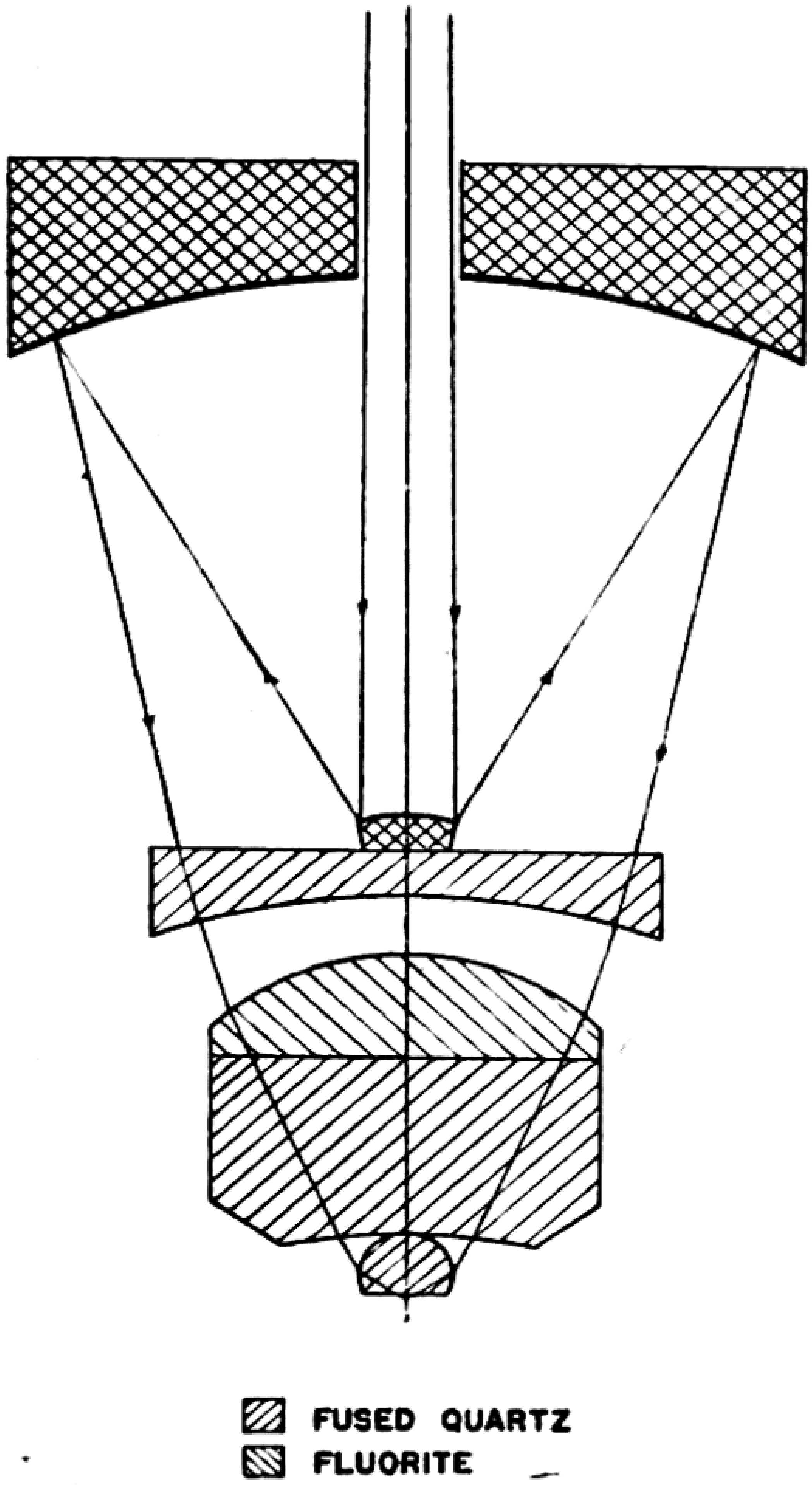

Fig. 6.2. A catadioptric Schwarzschild system with very low obscuring ratio. Spherical lens surfaces combined with spherical mirrors can permit the Schwarzschild system to have an obscured numerical aperture which is less than one-fifth the numerical aperture of the objective, giving less than four per cent. obscured area.

If refracting elements are to be used, it is most desirable that one lens element be placed adjacent to the convex mirror and between that mirror and the object. It is then possible to cement the convex mirror to the lens and thus eliminate opaque and occluding supporting structure. It was further hoped that refracting elements could at least to some degree substitute for the aspheric deformation of the Burch objectives. This would further reduce the occluded aperture of completely spherical systems and would permit larger numerical apertures by reducing zonal aberrations.

The extent to which occlusion may be reduced by lens elements in an all-spherical system is apparently limited only by the ratio of physical size to focal length which is to be permitted. This contention is illustrated by the system of Fig. 6.2. This combination was designed for use as a substage condenser of numerical apertures ranging from 1·25 down to 0·7. In order that the occluded fraction of aperture be small at NA 0·7, it must be extremely small at NA 1·25 (for the physical size of the convex mirror cannot be altered when the numerical aperture is varied in use). The occluded area is but 4 per cent of the exit pupil area. The size of this system makes it inconvenient (though by no means impossible) as an objective. Hence no great effort was spent in reducing aberrations—zonal aberrations are more than adequately corrected for a condenser. It certainly could be adequately corrected as an objective of NA 1·0, and possibly even at about NA 1·2.

Since the fraction of obscured area can be extremely small, but apparently only at the price of large physical dimensions, it is desirable to establish an upper limit to this defect. I have proposed* that 10 per cent of the exit pupil *area*, more or less, is an adequate and reasonable obscuration tolerance. This figure is supported through theory and by experiment, the latter by T. Dunham, Jr.†

In the early course of computing these objectives it became apparent that the lens elements can bear important duties other than to serve as a substitute for aspheric surfaces. As previously mentioned it does not seem possible with lens media known today to compute a refracting ultraviolet objective for which the position of a *real* object and a *real* image are nearly independent of wavelength within the tolerance which is often desirable. A refracting system of fluorite or lithium fluoride achromatized by fused quartz (or halide crystals) will have secondary spectrum of ordinary sign—the foci will be further from the objective at the extremes of a spectral interval than at the middle of the interval. On the other hand, if the image is *magnified*, but *virtual* rather than *real*, the following interesting properties are possible :

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* *J. Opt. Soc. Amer.* **39,** 727 (1949).

† Special Report No. 2, American Cancer Society Grant No. PH–1B Massachusetts Institute of Technology (1948).

1. Longitudinal chromatic aberration may be corrected by surface-separation even if only one refractive medium is used. If only one refractive medium is used, secondary spectrum is *anomalous* in sign, and the amount of magnification possible is dependent on the amount of variation of magnification with wavelength which is permitted.

2. The anomalous secondary spectrum peculiar to such a system as that above may be compensated by adding lenses of net positive power achromatized by using media of high and low dispersion, such as fused quartz and fluorite. These components further increase the magnification of the refractive system, but the image remains virtual.

3. If the refracting elements are of fused quartz and fluorite, the magnification at the virtual image thus formed may conveniently be as large as 2·5. Residual first order, or Gaussian, shift of focal surfaces with wavelength may then be of tertiary spectrum character, and more than adequately small over the interval 220 mμ into the visible spectrum.

When the *refracting* components have thus magnified the object, the *reflecting* portion of the objective is then required to operate at a numerical aperture equal to that of the objective as a whole, divided by the magnification realized through refraction. This gives two important benefits. First, the higher order aberrations of the mirrors, which lead to zonal aberrations, are in effect divided by the fifth plus higher powers of the refractive magnification. Second, the tolerance on positioning the mirror surfaces, which can be severe at large aperture, is more generous by a factor proportional to the third plus higher powers of the refractive magnification. Refractive components may thus supply well over half the power of the objective; and, moreover, they operate at the most crucial position—adjacent to the short conjugate focus. These benefits are in addition to substituting for non-spherical mirrors.

Aberration-Control in Catadioptric Schwarzschild Systems

The study of aberration control in the design of catadioptric Schwarzschild objectives divides naturally into two phases. First, one should find an arrangement of lens components which will compensate the primary (i.e. third-order) spherical aberration and coma of low-obscuration spherical mirror combinations. To permit low obscuration, the lens elements should provide either outward coma (at the long conjugate focus and with stop at the convex mirror) or over-corrected spherical aberration. In the objective of Fig. 6.3, outward coma is provided by the lens at the hole in the concave mirror. In the objective of Fig. 6.4 lens elements provide over-corrected (primary) spherical aberration. An objective of extremely small obscuration can be conveniently realized by either of these means if the separation between the mirrors becomes large. The length and diameter of the system then increase but there is no difficulty in maintaining control of aberrations.

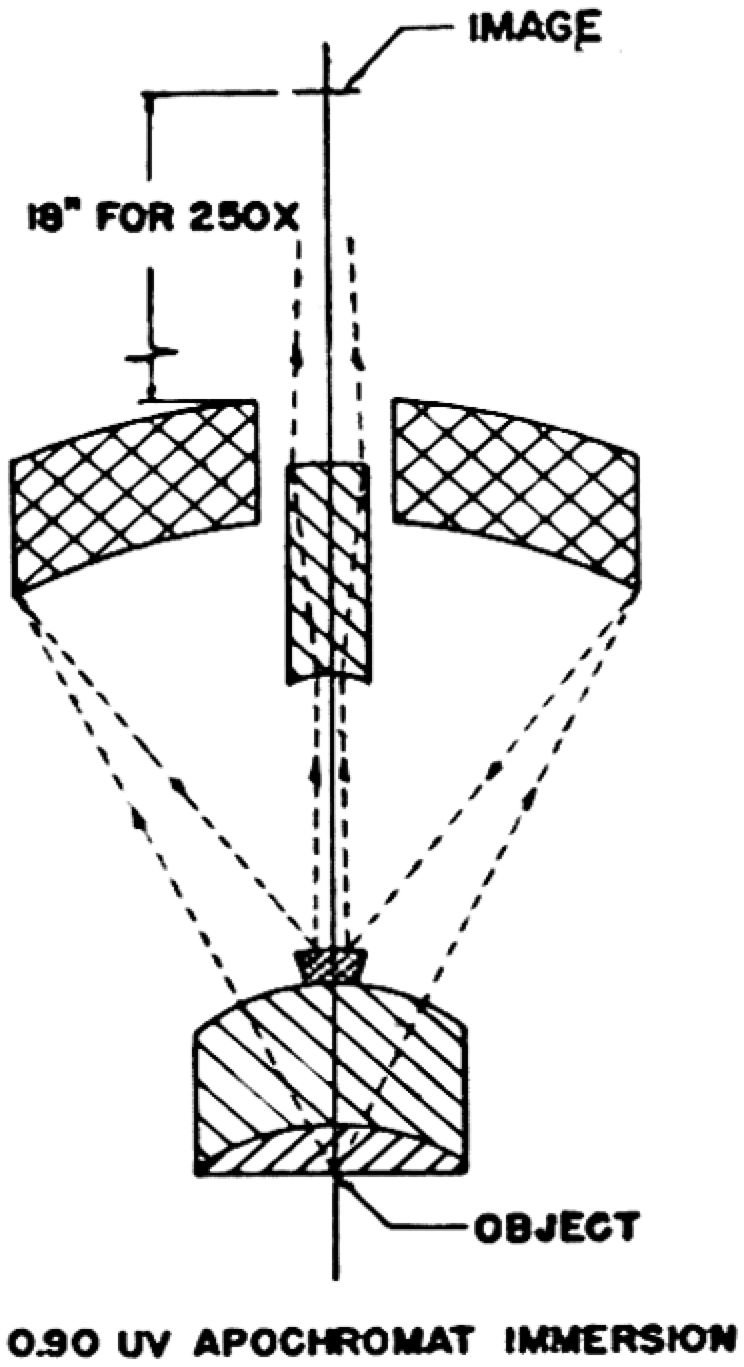


FIG. 6.3. The spherical Schwarzschild mirrors may be arranged to give low obscuring ratio if lens elements contribute outward coma or overcorrected spherical aberration. The lens at the hole in the central mirror gives outward coma. A further feature of this lens is that it compensates the variation of magnification with wavelength caused by the immersion component. The image formed by this objective may be photographed directly.

The second phase of aberration control is the reduction of high order spherical aberration, coma and chromatic aberrations. The aberrations which must in general be treated follow, and are perhaps most easily handled if attacked in the order of listing. They are: zonal spherical aberration, variation of primary spherical aberration with wavelength, and variation of higher order spherical aberration with wavelength; zonal coma, and variation of primary and of higher order coma with wavelength. The variation of refractive index from 220 mμ to the visible is so large that very often it is necessary to find separate control over both the primary and the higher order variation of aberration with wavelength.

Zonal spherical aberration may readily be overcome by placing a lens of large undercorrected primary spherical aberration close to the object as surface R_1 in Fig. 6.4. In the absence of such a surface, higher order spherical aberration (caused by the mirrors) will be overcorrected. This surface can reverse the sign of higher order aberration, so that appropriate positioning of this surface, proper selection of primary spherical aberration, and choice of a plane of best focus will bring three zones to a common focus. Judicious use of this procedure can render phase shift at the intermediary zones more than adequately small.

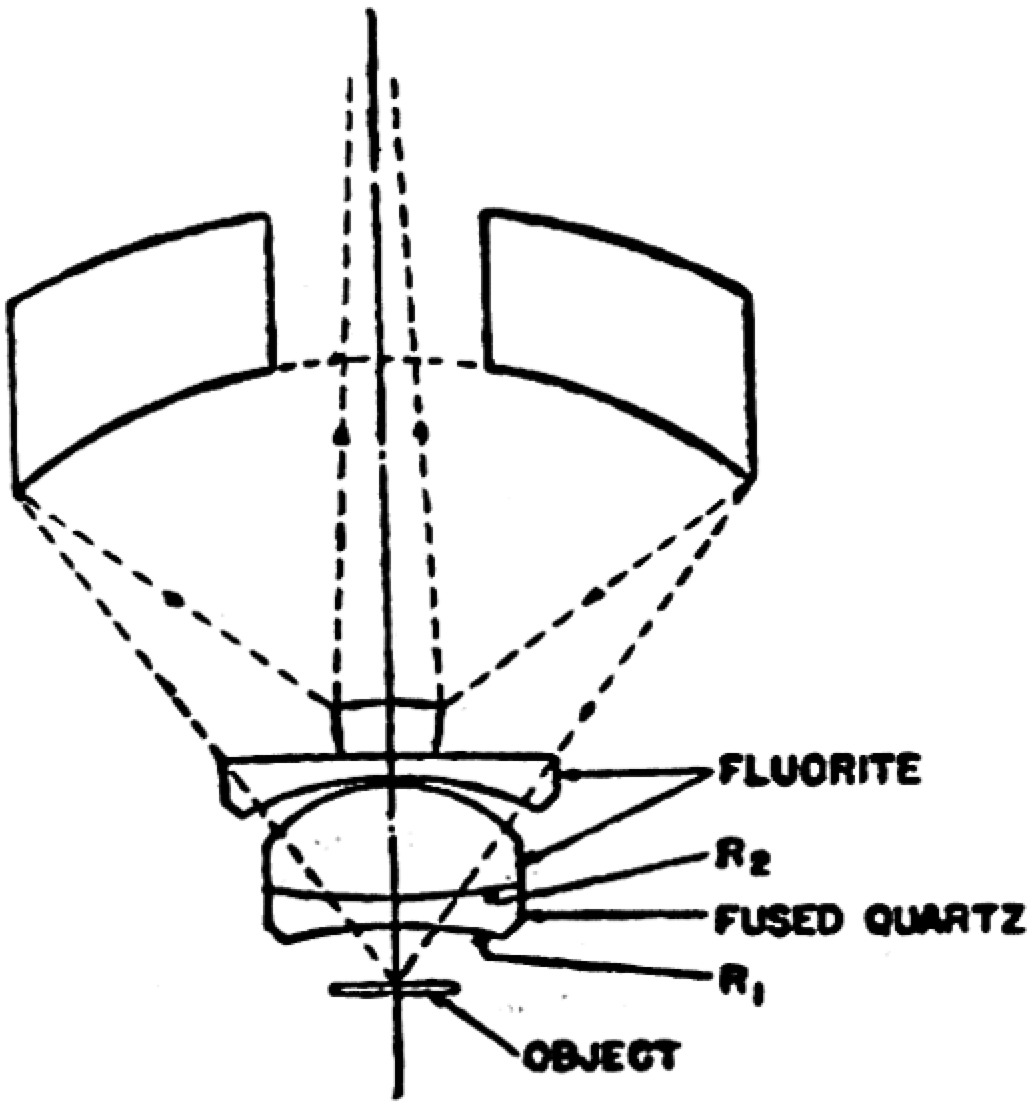
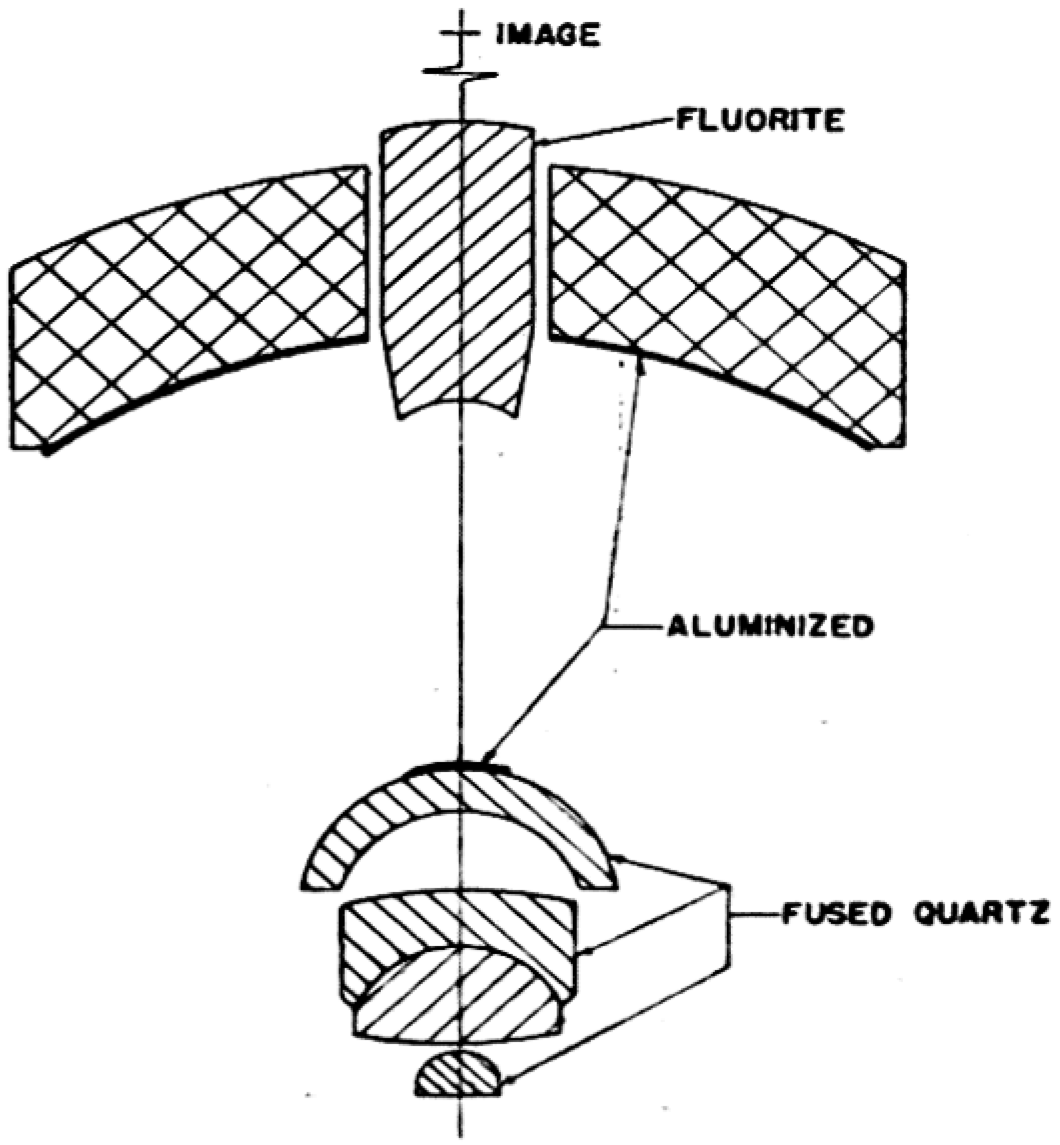


Fig. 6.4. This system permits low obscuring ratio by reason of over-corrected (primary) spherical aberration from the lens group. Also, surface R_1 reduces zonal spherical aberration and surface R_2 removes spherochromatic aberration.

Primary spherochromatic aberration may be overcome through the usual methods applicable in refracting systems. In general, the surface mentioned immediately previously for control of zonal monochromatic spherical aberration will introduce higher order spherical aberration which is more undercorrected at short wavelengths than at long wavelengths. One easily visualised and useful method of compensating this difficulty is through use of a cemented surface, as surface R_2 of Fig. 6.4. A further possible and useful control over chromatic variation of aberration is the net amount of primary spherical aberration provided by the lenses to compensate that of the mirrors. If the lenses provide a net aberration of a given algebraic sign, one might expect that the magnitude of this aberration would increase at shorter wavelengths for which refractive indices are higher—this effect may or may not occur, depending upon how various other parameters of the system are simultaneously manipulated. The net aberration of the lenses can be used as a means of chromatic aberration control, but this method should be avoided if possible because it relates to the obscuring ratio condition.

Zonal coma may be adequately controlled in an immersion system of large aperture by placing the object at, or approximately at, the



DESIGN NO. 6 U.V. OBJECTIVE

Fig. 6.5. An objective in which the convex mirror is an aluminized area on the centre of a lens surface.

Amici point of the first (or immersion) component. This, in fact, is the only satisfactory method which we have found of controlling this aberration at apertures greater than NA 1. Other methods have been found, but they involve lens combinations which so maltreat the off-axis bundles of rays that unexpected oblique aberrations appear even at small angular fields.

Variation of higher order coma with wavelength has always been most difficult to control. This perhaps is merely because it has come last on the list for correction, and many otherwise available parameters are thereby occupied. In systems which use the Amici points of the immersion component, the amount of chromatic coma thus to be compensated is quite large. Each system in which it has been necessary to affect this aberration has required a different method. In general, the controls found appear to have this in common; they are an effect of interaction or cross-product between primary aberrations or chromatic aberrations, or both, at widely separated surfaces.

Methods of "Eliminating" the Convex Mirror

A type of objective which has been attempted more or less successfully is one in which the convex mirror is continuous with the surface which supports it. Then, the convex mirror is merely an aluminized spot on the centre of this lens and is thereby eliminated as a separate element to polish and to mount. The greatest difficulty to be overcome in this type of construction is that the mirror surface requires a much shorter radius of curvature than is desirable for a lens at that position (see Fig. 6.5). A lens with the same curvature as the mirror strongly refracts the light rays and introduces an amount of chromatic aberration difficult to remove with lenses closer to the short conjugate focus. Three methods of overcoming or alleviating this difficulty have been found. One method is to place a negative lens between the convex mirror and the long conjugate focus (Fig. 6.5). This lens provides some of the diverging power which otherwise must be solely at the convex mirror. The curvature of the convex mirror, and hence of the coincident lens surface, is then decreased.

A second method is to use a back-coated concave mirror (Fig. 6.6). The front, and hence refracting, surface of this element may easily provide sufficient chromatic overcorrection to compensate the chromatic undercorrection from a surface coincident with the convex mirror.

A third method is to increase the obscuring ratio. If the fraction of the aperture area which is obscured is permitted to increase to 13%, the chromatic aberration becomes controllable.

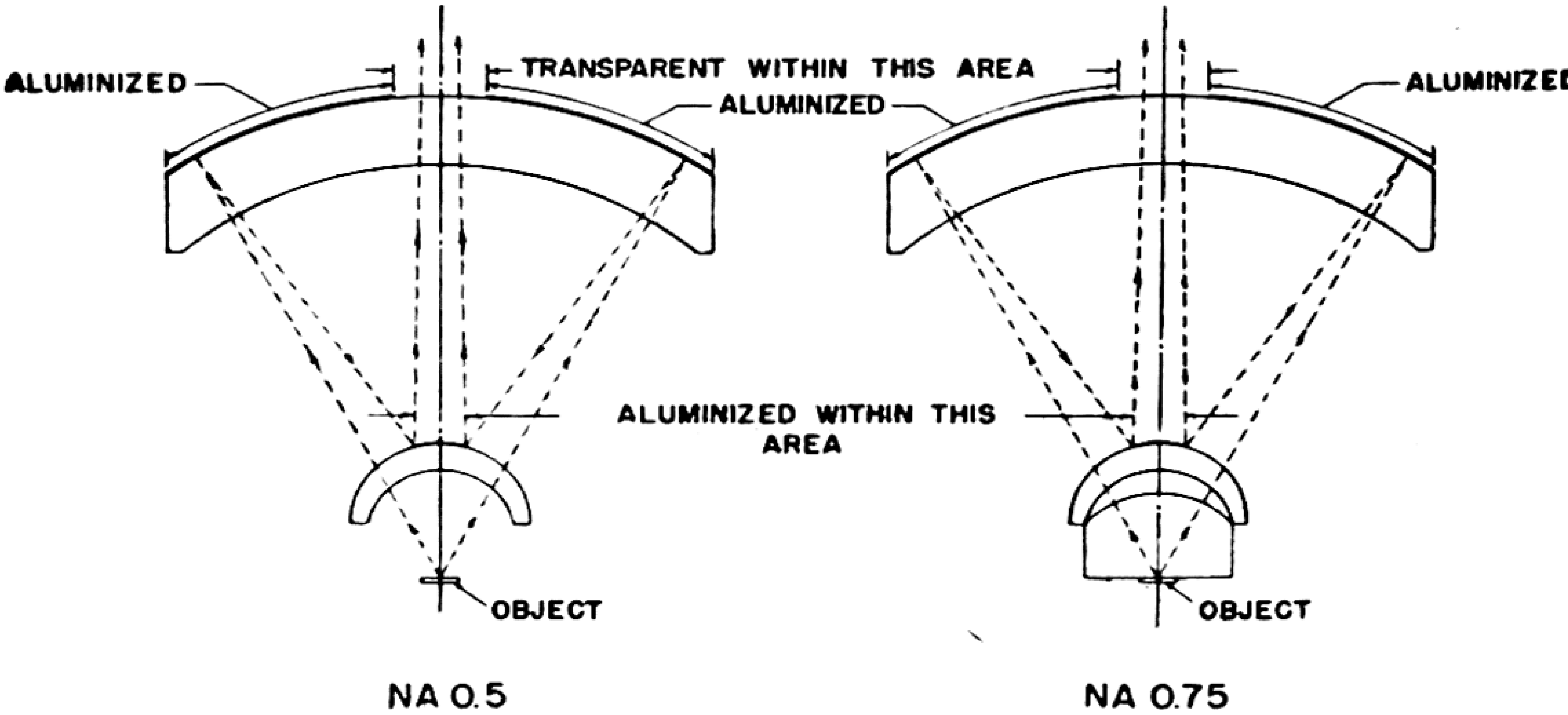


Fig. 6.6. The systems illustrate the use of a back-aluminized primary mirror.

A Series of Objectives

Our ultimate goal is a series of parfocalized objectives which will fit on to conventional microscope stands, and with numerical apertures from 0·4 to the largest we can realize. The magnification of the objectives will be approximately proportional to the numerical aperture, with 100× at numerical aperture of unity. Two sets of image enlargers which project the primary image on to a photographic plate or other image recording mechanism will be desirable, for the immersion objectives have a larger residual lateral chromatic aberration than do the dry objectives.

A lens element is placed at the hole in the concave mirror to seal the objectives against dust on the mirrors. This lens may be curved and thereby introduce a certain amount of lateral chromatic aberration. This expedient has aided in reducing the required number of eyepieces to two sets.

The objectives already computed are of NA 0·4, 0·7 and 1·0. Work now in progress on computing the final objective of the series indicates that it will have a numerical aperture between 1·2 and 1·3, the exact value depends on how well variation of higher order coma with wavelength can be handled.

A condenser suitable for illuminating the object for the objectives of NA greater than 0·7 has been shown (Fig. 6.2). The obscured aperture of this condenser is too large for illuminating the NA 0·4 objective. The two components nearest the specimen may be removed for this aperture, and replaced by a lens which duplicates the aberrations of the lenses shown but gives less converging power.

Infrared Objectives

The same principles of design described previously may be applied to infrared microscopy. At the instigation of Dr. Blout of the Polaroid Corporation, a series of infrared reflecting objectives has been computed. These objectives serve to throw a magnified image of the specimen on to the entrance slit of a spectrometer.

Because of the larger tolerance on optical design at the longer wavelengths, it is possible to achieve a larger numerical aperture with the spherical mirrors alone than for ultraviolet. We are using a spherical two-mirror objective of NA 0·63. The numerical aperture could be larger, but has been held to this value so that the visual image would be adequately sharp for purposes of alignment and focus.

A further design advantage peculiar to infrared microscopy is that the initial magnification of the objective may be low. When the initial magnification decreases, the obscuration of aperture decreases. The NA 0·63 objective has initial magnification of 8×, and as a result the obscured fraction of the exit pupil area is 12% (neglecting mirror supports). This is to be compared with approximately 20% obscured area for high magnification.

SOMMAIRE

Un objectif de microscope doit donner d'un objet réel une image réelle. Il ne semble pas possible avec les matériaux refringents actuels de calculer un objectif refringent pour l'U.V. et pour lequel les positions de l'objet et de l'image réels soient sensiblement indépendentes de la longeur d'onde, avec la précision désirable. On peut affirmer que les objectifs réfringents de grande ouverture numérique destinés à l'U.V. ont une aberration chromatique trop élevée.

L'impossibilité théorique de le correction des aberrations chromatiques disparait si l'image est virtuelle. On decrit une famille d'objectifs dans lequels on utilise des lentilles de fluorine

SUMMARY

et de quartz fondu à faces spheriques pour projeter une image achromatique aggrandie mais virtuelle de l'objet. Des miroirs sphériques convertissent ensuite cette image virtuelle en une image réelle.

Les aberrations monochromatiques du groupe de lentilles et du groupe de miroirs sont importants mais virtuellement compensées. Les données suivantes permettent d'ajuster le groupe réfringent au groupe catadioptrique :

1. aberration sphérique de chaque groupe
2. coma
3. le grandissement des miroirs

Ces parametres sont très utiles pour la correction des aberrations zonales aux grandes ouvertures et peuvent permettre d'utiliser des systèmes refléchissants dans lesquels le miroir secondaire n'obtenue qu'un faible fraction de l'ouverture de l'objectif. Des méthodes de reduction des aberrations en fonction de ces parametres sont discutées.

A microscope objective is required to present a real aerial image of a real object. It does not seem possible to compute a refracting objective which operates with ultraviolet radiation, and for which the positions of a real object and a real image are nearly independent on wavelength within the tolerance which is often desirable. Thus it may be said that refracting objectives of large numerical aperture and for use in ultraviolet have excessive chromatic aberration.

The argument against the possibility of chromatic correction breaks down if the image is virtual. A family of objectives will be described which use spherically curved lenses of fluorite and of fused quartz to form a magnified and achromatic, but virtual, image of the object. Spherically curved mirrors convert the virtual image into a real image.

The aberrations of the lens group and of the mirror group are both large, but mutually compensating. There are the following three parameters in the relation between the lens group and the mirror group :—

(1) The net spherical aberration of the mirrors.
(2) The net coma of the mirrors.
(3) The fraction of total magnifying power provided by the mirrors.

These parameters are of great value in correcting zonal aberrations for large numerical apertures, and in permitting mirror combinations for which the secondary mirror obscures but a small fraction of the objective aperture. Methods of aberration control dependent upon these parameters will be discussed.

GRATINGS AND GRATING INSTRUMENTS

7. Echelle Spectroscopy

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ECHELLE spectroscopy has recently been developed in an attempt to extend to routine spectroscopy, whether in the laboratory or in the works, the advantages of interferometry without its attendant disadvantages. The *echelle* is in effect a ruled interferometer, and receives its name from the fact that its properties lie between those of the diffraction gratings called *echelettes* by Wood,[1] and the reflection *echelon* as developed by Williams[2] at Adam Hilger, Ltd., from principles enunciated by Michelson[3]. An echelle can be used to increase the dispersion and resolving power of any existing stigmatic spectrograph by any desired factor up to fifty or more, while decreasing its speed by a factor not much greater than two. Echelles can also be used in conjunction with prisms to produce very compact spectrographs having resolving powers equal to those of the largest concave-grating installations, with a gain in photographic speed of ten or more. Especially important, it now appears that large echelles can be produced more readily than diffraction gratings or prisms of equivalent power, and should soon be generally available.

The considerations leading to the design of the echelle have previously been described by Harrison.[4] Since the resolving power of a dispersive interferometric device depends on the product of the number of interfering beams N and the order of interference m, high resolution can in theory be obtained by causing many thousands of beams to interfere in relatively low orders, as from the first to the twentieth in the diffraction grating, or by causing a few dozen beams to interfere in orders from the 15,000th to the 90,000th, as in dispersing interferometers. In practice, however, the interferometers give resolving powers ranging above one million, whereas no ruled grating now in existence gives values of $\lambda/d\lambda$ in excess of 400,000. This fact suggested the desirability of applying interferometry to routine spectroscopy, for which improved resolution is of the highest importance, especially when combined with increased compactness and optical speed. However, all previously available types of interferometers were found to suffer from such limitations as difficulty of adjustment, wastefulness of light, or complexity of the spectrum produced, and all possessed the inherent weakness of severely limited free spectral range.

Free spectral range, defined as the range of spectrum lying between successive orders of any given spectral line, affects greatly the ease with which one can identify lines in even fairly simple spectra. It is given by the formulae $F_\sigma = \frac{1}{2t}$ and $F_\lambda = \frac{\lambda^2}{2t}$, in wave numbers and wavelengths respectively, where $2t$ is the optical path difference between successive interfering beams. In all standard interferometers t is of the order of a few millimetres, so the usual free spectral range for visible light is less than an angstrom. This small range causes serious overlapping of orders when a complex spectrum is being studied, and often results in a wasteful and confusing multiplication of interference fringes for each wavelength present, instead of a single line which is to be desired. In the echelle t has been reduced to a small fraction of a millimetre in order that free spectral ranges of from 20 to 400 wavenumbers may be made available. An auxiliary crossed dispersion is then used to separate the various orders, with the result that the entire spectrogram is freed of overlapping spectra. The most desirable property of the echelon, that of automatically throwing most of its light into a single order for each wavelength, is retained; thus useless multiplication of images is eliminated.

During the slightly more than a year's time that has elapsed since the desirability of the echelle was first brought to public attention,[4] the Bausch & Lomb Optical Co. has developed a process for manufacturing these devices, with results that indicate that echelle spectrographs and special purpose echelles can soon be made available. Echelles giving resolving powers up to 300,000 have been produced by David Richardson and Gilbert Sheldon of the Bausch & Lomb Optical Co. with a special ruling engine built by D. W. Mann of Lincoln, Massachusetts, and preliminary tests of

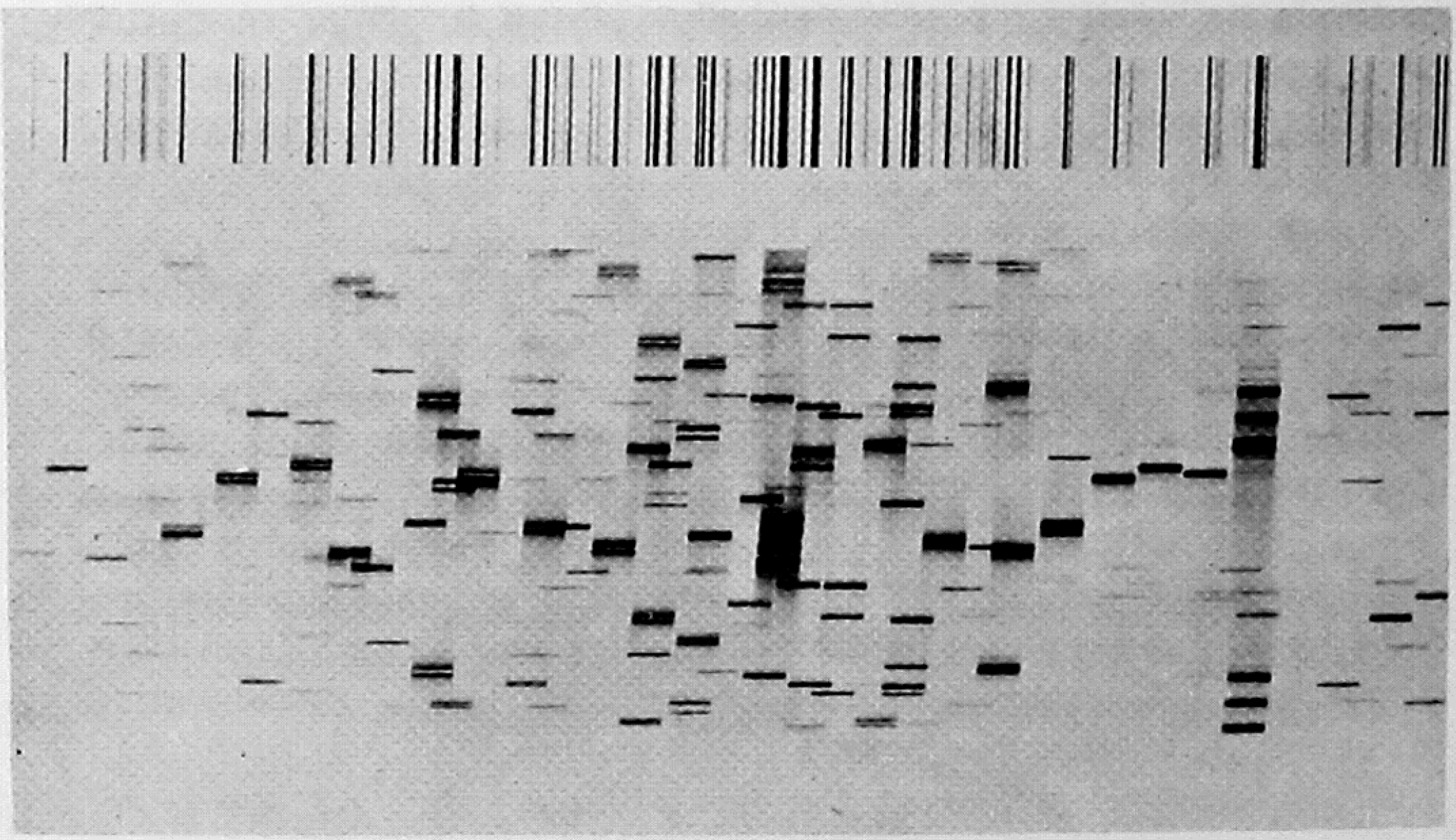
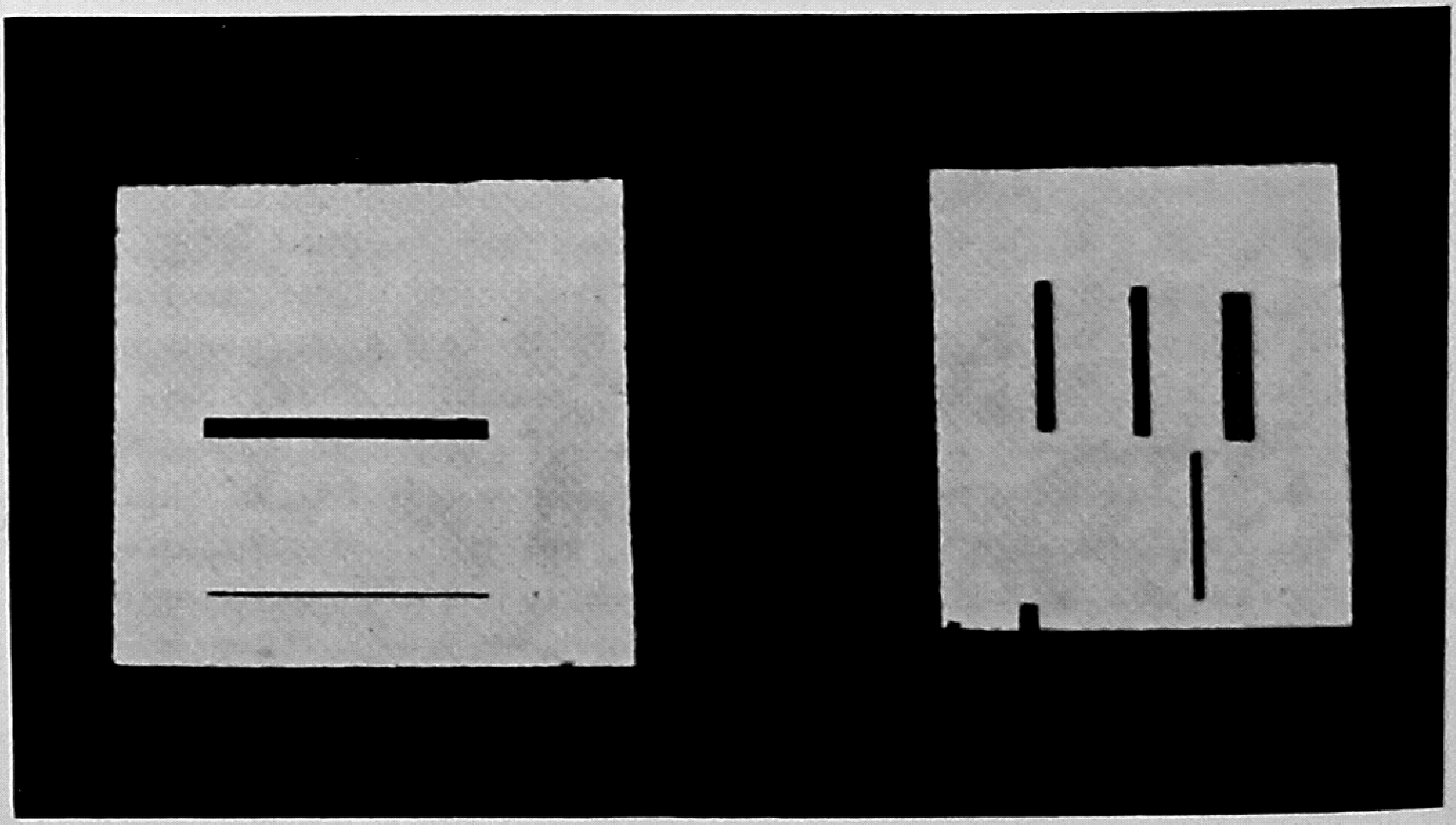


FIG. 7.1a (above). A portion of the iron spectrum between 3140A and 2895A photographed with a quartz prism Littrow spectrograph.

FIG. 7.1b (above). The same spectrum photographed with the same spectrograph whose dispersion has now been crossed with that of an echelle.

FIG. 7.2a (below). Enlargement of the 3100 iron triplet made with a quartz prism Littrow spectrograph.

FIG. 7.2b (below). The same crossed with an echelle.



methods designed to produce echelles of much higher resolution have been encouraging. The special processes used to produce satisfactory echelles will be described when they have been reduced to a routine basis.

A typical echelle spectrogram is reproduced in Fig. 7.1. Exposure (*a*) shows the iron spectrum from 3140 A.U. to 2895 A.U. as photographed with a Bausch & Lomb large quartz Littrow spectrograph in the usual manner. Spectrum (*b*) was taken with the same instrument, but with its dispersion crossed by that of an echelle. Each horizontal 40-wavenumber section of spectrum (*a*), less than 1 mm. in length, is drawn out in spectrum (*b*) into a strip more than ten times as long, with a corresponding increase of resolution. Whereas the plate factor of the prism spectrograph at 3100 A.U. is about 4·8 A.U./mm., use of the echelle raises the dispersion in spectrum (*b*) so that the plate factor becomes 0·35 A.U./mm., and the resolution is increased correspondingly. Fig. 7.2 shows an enlargement of the 3100 A.U. spectral region with and without an echelle; the 3100·666 A.U., 3100·304, and 3099·934 lines of iron, the " triplet " long used by spectrograph manufacturers to test the excellence of their quartz Littrow prisms, are barely resolved in the first case; with the echelle even the lines 3099·971 and 3099·897 A.U. are resolved.

The advantages of such an arrangement for spectrographic analysis are obvious. An echelle spectrogram can first be made to determine whether or not unknown or impurity lines interfere with the analytical lines to be used; then a low-dispersion spectrum can be photographed in the usual manner. Or the echelle lines can be used directly for analytical purposes, the high dispersion giving great reduction of background relative to line intensity, and thus improving the " signal-to-noise ratio " that sets the limit of sensitivity in a qualitative spectrographic analysis, and limits precision in those quantitative analyses where an unlimited sample is available but the concentration of the element being measured is low.

The echelle used in making the spectrograms shown measured 6 × 6 inches, though since it was illuminated with a lens of 3-inch aperture, only an area of 3 × 6 inches was used. It contained 200 grooves per inch; thus 1200 beams interfered in orders ranging from the 725th at 3140 A.U. to the 785th at 2895 A.U.

In Fig. 7.1b slightly more than one echelle order is included in each vertical cycle, so that many of the line patterns are seen repeated, somewhat more weakly, in another order. Owing to the use of the crossed-dispersion, however, this results in clarification rather than confusion, and such repetition can be reduced to any degree desired by giving special attention to the flatness of the echelle steps.

Echelle Design Characteristics

Fig. 7.3 shows the more important design parameters of an echelle. These are the ruled width W, the step depth t, and step width s. These parameters serve to control the resolving power $\lambda/d\lambda$, the dispersion $d\theta/d\lambda$, and the free spectral range F. In addition we are concerned with the projection distance P of the lens or mirror with which the echelle is to be used, and wish to know the length L of each echelle cycle on the plate.

The formula for resolving power at a given wavelength λ is most conveniently written $\frac{\lambda}{d\lambda}=\frac{2W}{\lambda}\left(\sqrt{\frac{r^2}{1+r^2}}\right)$, where $r=t/s$, the step ratio. The term in parenthesis can be neglected if we remember that when $r=2$ the resolving power will be reduced from $2W/\lambda$ by about 10%, when $r=3$ by 5%, and when $r=5$ by 3%. In practice the deviation of a given echelle from the limiting resolving power will be more adversely affected by lack of planeness and parallelism in its steps than by its r value. Thus far we have not achieved resolution greater than about 50% of theoretical, but values up to one million for visible light appear possible of attainment with echelles having as much as 12 inches of ruled width.

We may write the formula for the dispersion at the plate in the form $\frac{dl}{d\lambda}=\frac{2rP}{\lambda}$. Thus dispersion is very sensitive to step-ratio r, for r is the tangent of the angle of incidence and of reflection, and these angles control the dispersion of any grating, regardless of its "grating constant." The commonly accepted statement that the dispersion of a diffraction grating depends on its number of grooves per inch applies only *within a given order of interference*, and in the echelle limitations of order do not apply. Thus far all echelles that have been produced have had r values lying between 2 and 4, but values as high as 7 may prove practicable for certain purposes. In general, to increase dispersion one would raise r to the highest possible value so as to keep optical apertures and spectrograph size small; when raising r is no longer practicable, one goes to larger values of the projection distance P and designs a larger spectrograph.

To indicate the high dispersion attainable with an echelle we may within reason set $r=5$ and $P=5000$ mm., whereupon we obtain $\frac{dl}{d\lambda}=\frac{2 \times 5 \times 5000}{5000}=10$ mm./A.U. giving a plate factor of 0·1 A.U./mm. at 5000 A.U. and still higher dispersion at shorter wavelengths. By crossing such an echelle with a 30° quartz prism of moderate size, we would obtain a spectrograph more powerful than the world's best 10-metre concave grating installation which could be enclosed in a case less than 18 ft. long and not more than 2 × 2 feet in cross section. This would have less than 1/100th the volume of a concave grating installation of equivalent coverage, and would be many times faster because of the absence of astigmatism. Furthermore, because of the cyclic character of the echelle-prism spectrogram, the entire range from 2000 to 10,000 A.U. could be photographed on fewer than one-tenth as many plates as would be required for the grating installation.

In almost any echelle design problem, choice of free spectral range must be made first, for this to a considerable degree depends on the character of the auxiliary dispersion to be used. Prism dispersion is superior to grating dispersion for this, both because it is easier thus to obtain a stigmatic spectrum, and because the dispersion of the prism is more nearly uniform on a wavenumber basis, to fit the cycles of the echelle, than is that of a grating. The free spectral range of the echelle in wavenumbers divided by the dispersion of the prism system in wavenumbers per mm. gives the length in mm. of the allowable spectrum lines if overlapping of cycles is to be avoided. Unless the spectrum is very dense with lines, some overlapping is not objectionable, as is seen in parts of Fig. 7.1.

We have found uses for echelles with step depths t ranging from 0·23 to 0·012 mm., giving free spectral ranges of from 21·7 to 417 wavenumbers. We have thus far produced only echelles having step depths from 0·23 to 0·057 mm., having from 100 to 400 steps per inch. The larger the value of t, the easier is the control of the flatness of the individual reflecting steps.

We are preparing to rule echelles with as many as 2000 steps per inch to raise the free spectral range to the point needed for the design of spectrographs of very short focal lengths having low crossed-dispersion.

The minimum desirable length of groove of an echelle may be calculated by multiplying $\frac{1}{\sqrt{r^2+1}}$ times the ruled width W. However, where sufficiently large auxiliary optical parts are available it may be useful to rule longer grooves for the sake of the extra aperture so made available thus increasing speed without affecting resolution.

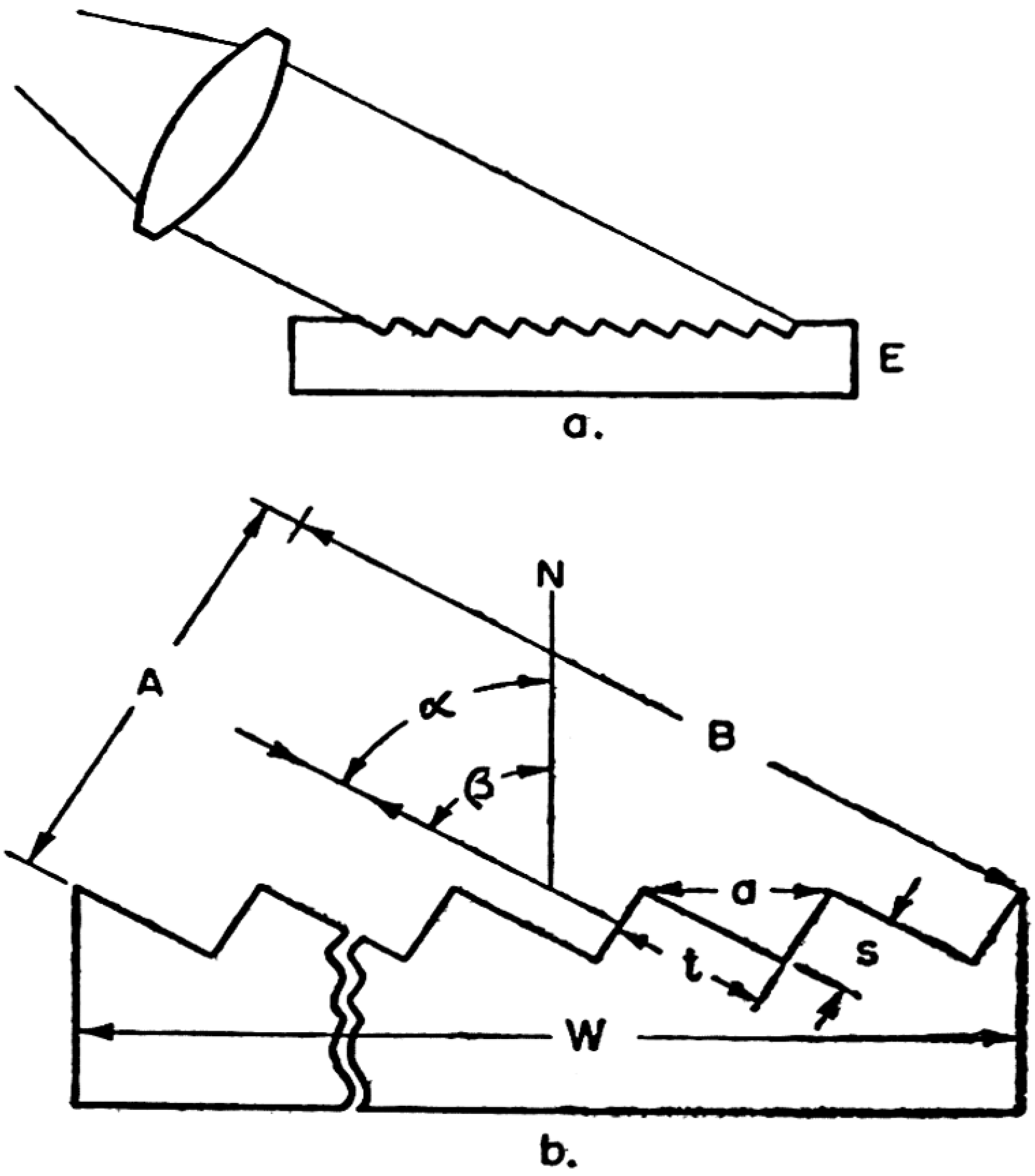


FIG. 7.3. (a) Mode of illumination of echelle in the Littrow mount with parallel light. (b) The design parameters of an echelle E; W, the ruled width of the echelle; B, its optical depth; A, its optical aperture. These quantities are respectively N (the number of grooves) times a, the groove separation; t, the groove depth, and s, the groove width. α and β are the angles of incidence and reflection of the light used to illuminate the echelle.

Speed of Echelle Spectroscopes

The echelle may be thought of as a plane reflection grating in which diffraction effects and spreading of the spectrum in angle have been reduced to a minimum; which has been designed to be used at large, constant, and equal angles of incidence and reflection; and which has the property of concentrating a high proportion of the radiation of any given wavelength falling on it into a single spectrum. It differs from the echelette in that the latter is "blazed" so that the radiation it diffracts is concentrated as much as possible into those *orders* which are to be used; since blazing is a directional effect rather than one primarily related to order, a given echelette can be blazed for only a limited range of wavelengths. Blazed gratings which are ruled to be "bright" in the first-order visible are usually found to be weak in the first-order ultraviolet, and as many as a dozen different echelettes are needed to cover much of the infra-red region with proper intensity. Since the echelle throws all its spectra into a narrow cone of radiation pointed in one direction, if blazed for one wavelength it will automatically be blazed for all. In theory more than 80% of the light of any wavelength can be concentrated in a single order. Whether this will be true for all desired wavelengths from a particular echelle is a matter of probability. The worst possible case is when some lines may fall in the double order position shown as a and a^1 on Fig. 7.4.

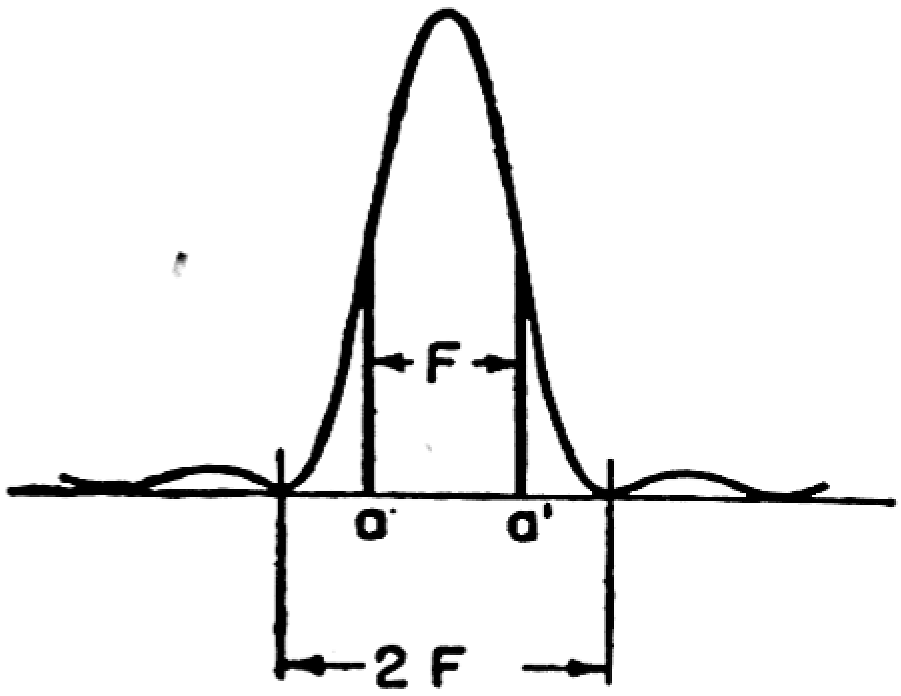


FIG. 7.4. Distribution of monochromatic radiation diffracted from one step of an echelle. The distance $2F$ represents two orders or free spectral ranges. The part of the spectrum used is that comprised within the width F. In the extreme case the same line may appear twice at the double order position a and a^1.

The distribution of intensity from an echelle with perfectly flat steps is that given by diffraction theory from a mirror having dimensions of a single step of the echelle, as shown in Fig. 7.4. Most of the light is thrown into a single order, and the intensity falls rapidly on each side of the central maximum. In actual practice the edges of the echelle steps are slightly rounded, which throws light into neighbouring orders. Our first echelles spread the intensity of the mercury line 5461 A.U. fairly evenly among fifteen or twenty orders; gradually the flatness of the steps was improved, and the later echelles gave excellent concentration. The best energy distribution attained thus far is that of echelle No. 16, which has an energy curve for Hg 5461 A.U. measured photoelectrically as shown in Fig. 7.5. Here 36% of all the energy in orders between 385 and 408 goes into the main order, the immediately adjacent orders to left and right share 24%, and the remaining 40% is distributed among the other orders. It is easy to occult all spectra except the principal one, so the only effect of imperfect concentration of energy is a reduction in optical speed. Our present experiments indicate that concentrations in excess of 75% for the " single order position " should not be difficult of attainment.

Echelle Spectrographs and Monochromators

The high intrinsic resolving power of the echelle makes available gains which can be realized as improvements in dispersion or photographic speed or compactness of spectroscopic instruments, or all three. These gains are especially valuable for research spectrographs of high resolving power, broad-range spectrographs and photoelectric spectrometers for analytical work, and infra-red spectrometers and monochromators for the visible, infra-red and ultra violet.

The echelle appears to lend itself more effectively to production in large sizes than does either the diffraction grating or the dispersing prism. For applications in which high radiant flux is important, it seems probable that much larger spectroscopic instruments than are practical at present can be made with echelles as the principal dispersing device. A limitation at present is the requirement of an auxiliary dispersing element, usually a prism, but prisms of small angle can be made in larger sizes more conveniently than can the thick prisms needed when they are to furnish the necessary dispersion alone. In monochromators used with a continuous spectrum of radiation, use of an echelle giving a tenfold increase in dispersion over a prism instrument makes it possible to widen both entrance and exit slits ten-fold without loss of spectral purity, with a resulting hundred-fold increase of radiant flux. If improved spectral purity is desired rather than more flux, the slits can be narrowed again.

The echelle must be illuminated with parallel light, and therefore requires a lens or concave mirror for collimation of the beam from its slit. For greatest flexibility of use an echelle can be mounted in its own specrograph, light from the exit slit of which can then be used to illuminate any ordinary stigmatic spectrograph, the dispersion of the two instruments being crossed. Since the echelle spectrum is never more than an inch or two long, with the entire

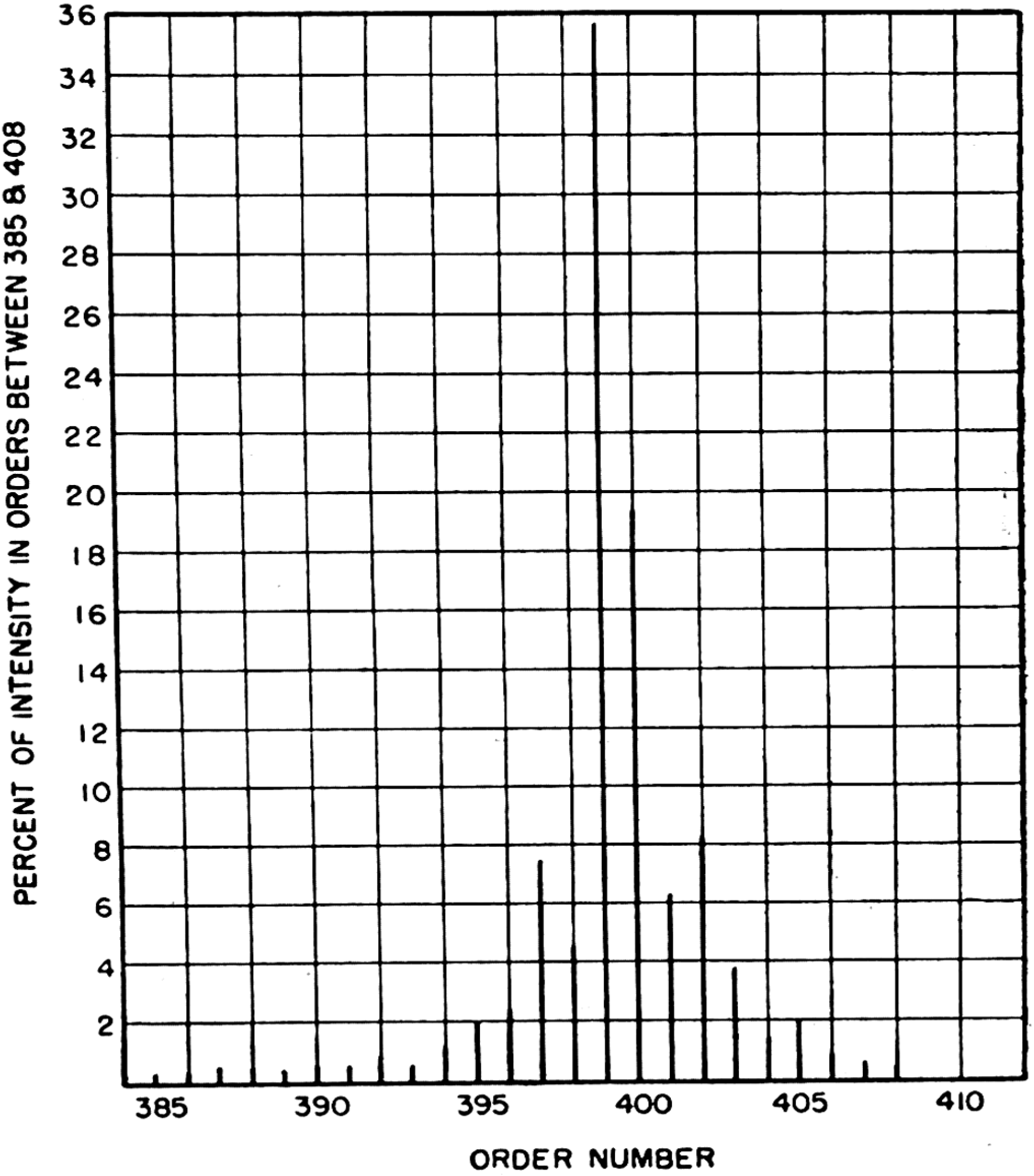


Fig. 7.5. Energy distribution from a typical echelle measured photoelectrically, using the mercury line λ5461 A.

spectrum piled up in unseparated cycles on the exit slit, chromatic aberration cannot be tolerated in the focusing system in this method. A well-corrected achromatic lens may be used in the Littrow system, as in Fig. 7.6a, or an aluminium-coated concave mirror can be used as in 7.6b. The first alternative is likely to be somewhat faster photographically than the second at wavelengths shorter than 2500 A.U. but if a high-quality aluminium coating is used on the mirror the transmission of the system, including reflection losses at the echelle, can be kept above 50% at all but the shortest wavelengths.

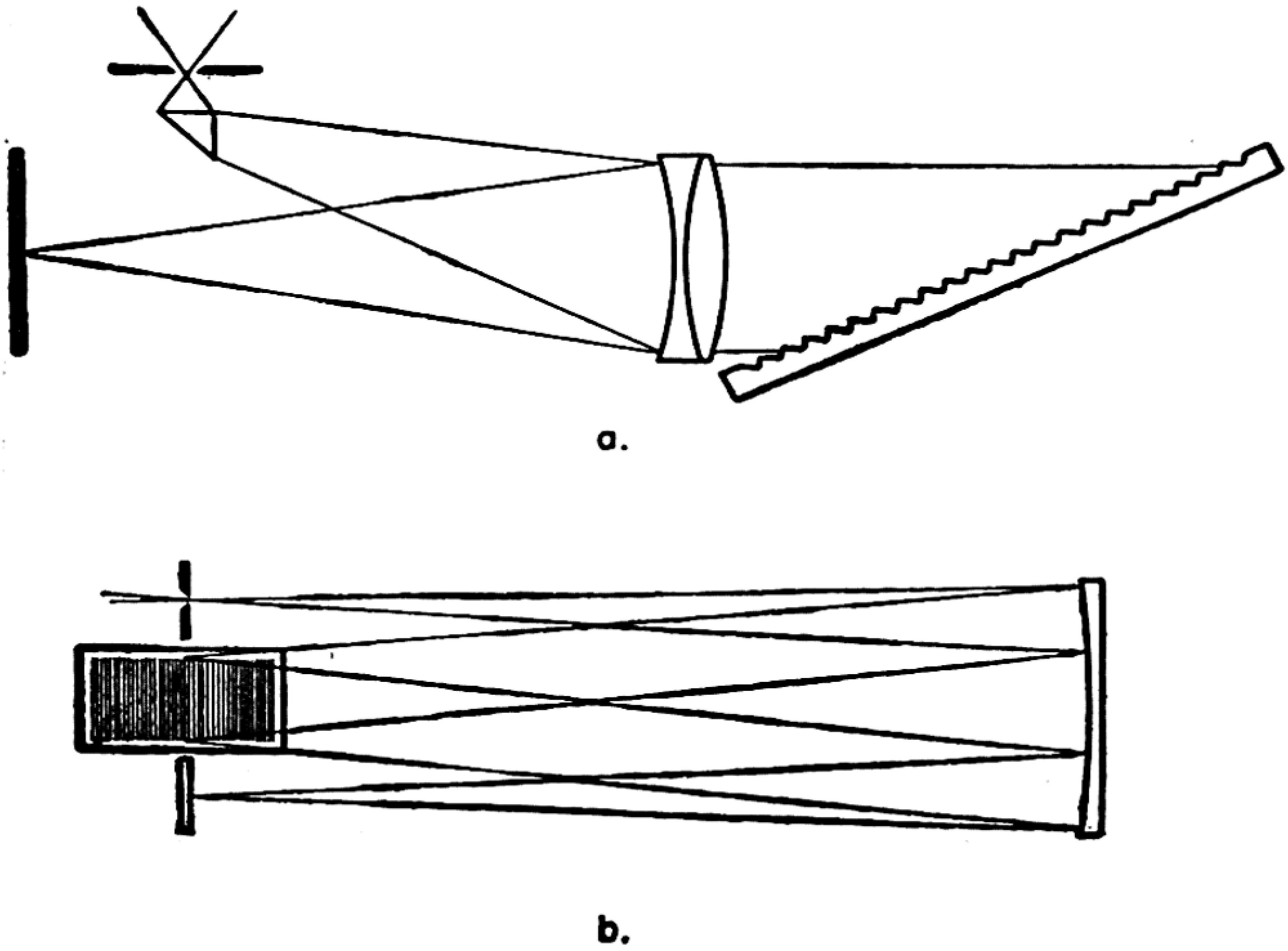


FIG. 7.6. Methods of producing an echelle spectrum for illuminating the slit of an ordinary stigmatic spectrograph. (a) Mounting using an achromatic lens. (b) Mounting using a concave mirror.

The entrance slit can conveniently be made horizontal and rather short, unless it is desired to send light from the echelle spectrograph into several other spectrographs simultaneously. The exit slit should be somewhat longer than is conventional (up to 50 mm. may be convenient) and as wide as the entrance slit is long. The exit slit should be readily removable so that the entrance slit of a low-dispersion spectrograph can be inserted in its place. However, the length of the echelle cycles on the plate varies linearly with wavelength, and may vary along a single plate in extreme cases by as much as five fold. It is therefore convenient to arrange to project the light from the first exit slit to the second entrance slit by means of a corrected lens or a mirror, and to change the magnification of projection in accordance with the spectral range being covered.

In a special arrangement for Zeeman effect work now being designed, light from a single echelle is being used to illuminate three spectrographs simultaneously so that the entire range from 2000 to 10,000 A.U. can be covered in a single exposure on three plates. A horizontal slit 4 mm. long is used with the echelle; one-third of the length of this slit provides light for a quartz Littrow spectrograph that covers 2000–3000 A.U.; the central third illuminates another Littrow for the region 3000–5000 A.U.; and the final third feeds a stigmatic concave grating mount that is used to photograph 5000–10,000 A.U. The echelle-spectrum radiation for the first spectrograph is magnified on projection by a factor of 2; that for the central region is projected without magnification, and that for the long-wave region is diminished on projection, to make most effective use of the slit dimensions of the auxiliary spectrograph in each case. Such an arrangement would be most effective in analyzing extremely small samples of material, where a high-dispersion broad-range spectrum must be produced by burning quantities of sample measured in micrograms.

A somewhat simpler mounting for an echelle consists in inserting it directly behind the prism of a commercial Littrow spectrograph. The reflecting coating can be removed from the Littrow prism and the echelle mounted at its proper angle behind the prism. Some slight loss in echelle resolution results with this arrangement, but in general it does not exceed 10%, and the sacrifice can well be made for the simplification and compactness that results. It is especially important that an echelle used in this way be extremely plane; if it introduces focusing power due to some slight cylindrical concavity or convexity, difficulty may be found in focusing the lens of the Littrow spectrograph in both the horizontal and vertical planes simultaneously. It will be noted that in this arrangement, shown in Fig. 7.7, an uncorrected lens can be used, and no exit slit is needed. Conveniently a reflecting mirror which can be slid into and out of position can be provided between the Littrow prism and the echelle. The Littrow spectrograph can then be used in the ordinaryway, with mirror in, and with the extra echelle dispersion with mirror out.

Reduction of Echelle Spectrograms

So much spectroscopic information may be compressed into a small area of an echelle spectrogram as to make the problem of identifying and comparing spectral lines appear difficult. The distribution of wavelengths follows such simple laws, however, that it is easy to avoid confusion. It is convenient to provide a viewing box for echelle spectrograms in which a slotted occulter covers all cycles except the one immediately under observation. Along each short echelle cycle the wavelength variation is sensibly uniform and we have a " normal " spectrum, so that linear interpolation between known lines serves when even the greatest accuracy is required. From cycle to cycle the dispersion changes linearly with wavelength. The value of t of an echelle can be accurately determined geometrically by means of two standard lines and the integral-order rule, and it seems probable that echelles can be made more free of " error of coincidence " than can ordinary gratings, so that wavelengths can be determined directly by geometrical means, as with an interferometer. A magnifying viewer with internal scale calibrated directly in angstroms can be provided, with variable magnification that can be adjusted by means of a knurled head carrying a wavelength scale. Rapid direct reading of accurate wavelengths should thus be possible. For wavelength determinations of the highest precision a two-way comparator should be used.

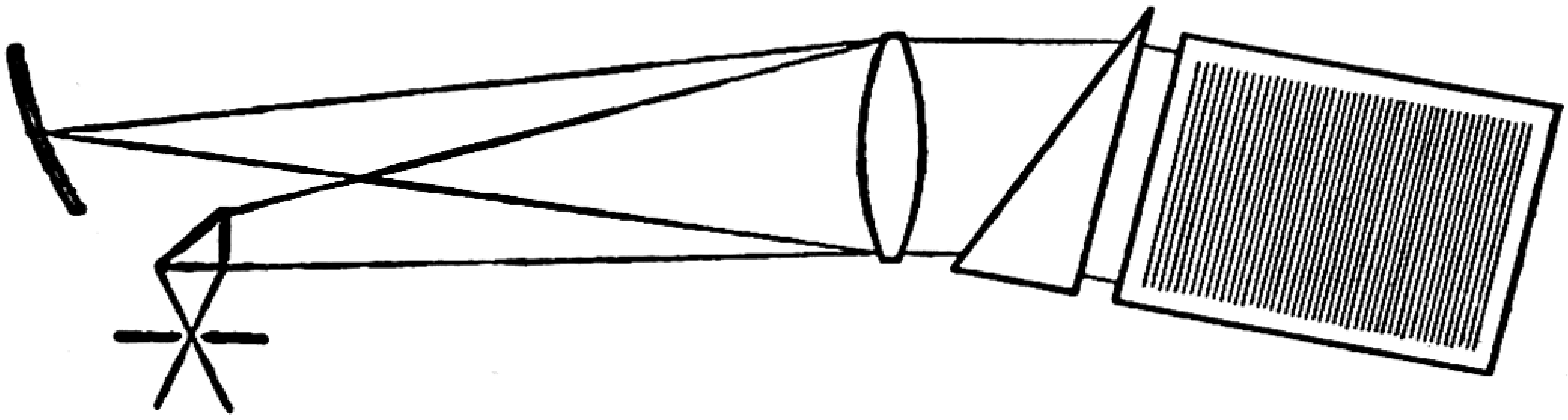


FIG. 7.7. Method of using an echelle in an ordinary quartz prism Littrow spectrograph.

The problem of introducing comparison spectra is not difficult, for at the high dispersion available with an echelle standard lines can be interleaved in most spectra without danger of undue confusion. In most analytical work only selected lines are compared in intensity, and these can be isolated by means of occulters to leave ample space for a multiplicity of exposures on a single plate. We have found no difficulty in producing lines with an echelle of sufficient area for routine densitometry.

Experiments on the production of larger and more perfect echelles of the types needed for the branches of spectroscopy outlined above are proceeding rapidly, and it is hoped that these useful devices can soon be made generally available.

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SUMMARY

Le pouvoir de résolution et la dispersion d'un réseau de diffraction ne dependent pas respectivement du nombre total de traits et du pas du réseau, mais seulement de la largeur striée du réseau et de l'angle de diffraction. Harrison a montré l'intéret que present un réseau plan, dont les traits ont des facettes planes et dans lequel on utilise des ordres variant de 200 a 1000. Les proprietés sont intermédiaires entre celles de l'échelon dont l'utilisation est limitée par l'étroitesse de la bande spectrale et l'échelette dont le pouvoir de résolution est relativement bas. De tels réseaux, appelés échelles, sont maintenant fabriqués et la qualité obtenue est, à certains égards, supérieure à celle de beaucoup de réseaux de six pouces. Des pouvoirs de résolution supérieurs a 300,000 ont pu être atteints. On peut concentrer plus du tiers de la lumière (quelle que soit la longeur d'onde) dans un ordre déterminé. Un réseau échelle associé à un objectif de petit distance focale permet d'obtenir une dispersion et un pouvoir séparatif superieurs a ceux d'un réseau concave de 10 metres utilisé dans le 1er. ou dans le 2e. ordre, et est de 10 à 20 fois plus lumineux, du fait de l'absence d'astigmatisme, la meilleure concentration de l'energie dans une direction et l'utilisation d'une ouverture numérique plus importante. Le réseau échelle est utilisé en croisant sa dispersion avec celle d'un spectrographe ordinaire, soit à l'exterieure soit en inserant l'échelle dans le faisceau de lumière parallèle du spectrographe, augmentant ainsi la dispersion utile de ce dernier de 10 a 15 fois, et en perdant très peu de luminosité.

The resolving power and dispersion of a diffraction grating do not depend respectively on the total number of ruled grooves or the number per inch, but only on the ruled width of the grating and the angle at which it is used. Harrison* has emphasized the usefulness of a coarse plane grating of plane-sided groove form, in which orders from the 200th to 1,000th are used. Its properties lie midway between those of the echelon, which because of its extremely small free spectrum range has limited usefulness, and the echelette, which has low resolving power. Such gratings, called echelles, are now being produced of a quality in some respects superior to that of most six-inched ruled gratings. Resolving powers in excess of 300,000 have been reached. Concentrations or more than one-third of the diffracted light of any given wavelength to a single high order have been attained. An echelle used with a lens of short focal length can be made to give higher dispersion and resolving power than a 10 meter concave grating used in the first or second orders, and is from ten to twenty times faster, owing to freedom from astigmatism, greater concentration of light in a given direction, and higher usable numerical aperture. The echelle is used with its dispersion crossed with that of any ordinary spectrograph, either externally or by inserting the echelle into the parallel beam of the spectrograph, thus increasing the useful dispersion of the latter from ten to fifty-fold with very little decrease in speed. Typical echelle spectra were shown.

* "Journal of the Optical Society of America," 39, 522 (1949).

8. A Grating Spectrograph with Interchangeable Receivers for Industrial Purposes

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AS is well known, several applications of photomultiplier tubes, such as RCA 931A and IP28, have recently been made in the construction of spectrographs. Thus spectrochemical analysis, in which the percentage determination of the elements present in a sample is performed by means of their spectral intensities, nowaday almost exclusively using photocells, as was first done by Lundegardh,[1] has reached a perfection sufficient for making it an important substitute for the chemical routine methods in metal industry laboratories and many other research centres.

The combination of this type of receiver with the Siegbahn grating as dispersing element has made it possible to design a spectrograph with small dimensions and general application.

The Grating and its qualities

The gratings used are ruled on circular blanks with a diameter of 100 mm., the ruling occupying an area of 40 mm. × 85 mm. The spacing is 17,400 A.U., and by means of the shape of the diamond the grooves are formed for concentrating the intensity into the wanted first order of reflexion on one side. The radius of the gratings will be either 1·0 or 1·5 metre, and tests are being made to decide definitely between these two alternatives. In both cases the dimensions of the spectrograph are sufficiently small to render it a convenient arrangement. Owing to the large aperture of the grating and its " blaze," the luminosity is very great, making the requirements for the electrical amplifiers fairly easy to fulfil.

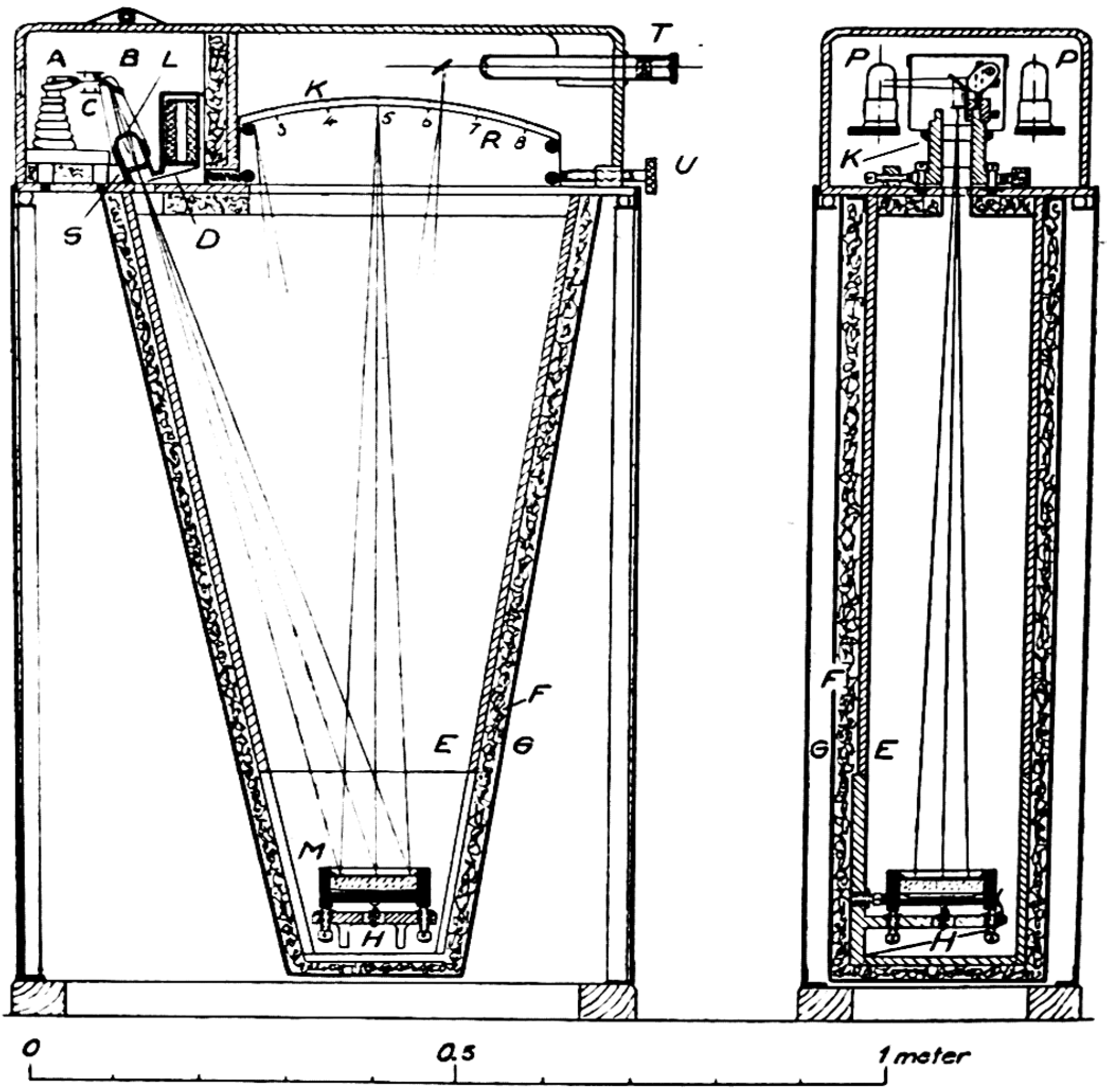

Fig. 8.1. General view of the 1 metre apparatus.

((*Note added in proof, November,* 1950 : The mechanical construction has been somewhat changed in order to give more space for different light sources, also for the acetylene flame with injected salt solution. Thus, the beam *SM* is nearly vertical, and the light source case has been built out.)

As recent measurements[2] have shown, the stray light amount in relation to the main intensity of the spectrum is less for a blazed grating than for an ordinary one, which is favourable if measuring on weak lines. In the lecture is also reported how the gratings are tested for periodic errors by means of a phase contrast method, giving a sensitivity proper for high-quality gratings where the errors, and thus the ghost intensities, are small.[3]

The general arrangement of the spectrograph is seen from the figure, showing the 1·0 metre model. The grating, in ordinary Paschen-Runge mounting, is placed at the bottom, so that the diameter of the Rowland circle is vertical. The entrance slit is placed at such an angle that the spectrum will lie around the opposite part of the Rowland circle, with perpendicular exit of the light. The domain of wavelength is 2000–8000 A.U. in the first order, the point of 5000 A.U. being opposite to the grating. The linear dispersion is, as an average, 17 A.U. mm. or 11 A.U. mm. for the two different radii.

To obtain great mechanical and thermal stability the mounting of the grating is arranged as a heavy ring *M*, adjustable in respect to the mounting-holder *H*. The holder is rigidly fixed to the wall of the spectrograph housing. This housing consists of a heavy aluminium wall *E*, surrounded by a thermal insulating layer consisting of a special micro-fibre glass wool *F* and its cover *G*. The overall dimensions of the spectrograph shown are 650 × 350 × 1300 mm.

The electrode stand *A*, applicable for different purposes, is constructed by the Research Institute of National Defense in Stockholm. To prevent particles from the light source damaging the optical system a tube with inside rings *C* is inserted near the light source. A mirror *B* of aluminized glass, easily movable in a metal frame, throws the horizontal light beam from the light source through the quartz lens *L* on to the entrance slit *S*. An electrically operated shutter *D* is placed near and below. As seen from the figure, the light source is enclosed in a separate insulated cover.

The Receiving Assembly

On the Rowland circle *R* is placed the cylindrical part of the slit-holder assembly *K*. On each of its sides there is a row of five photomultipliers *P*, on the sensitive targets of which the light from the slits is thrown by means of mirrors. Generally, a slit should be placed on the focussed spectral line of an element contained in the electrodes, and thus the arrangement will make it possible to obtain an analysis of nine elements present in a sample. Each slit is adjusted once for all to its proper position, and the mirror, which belongs to the slit system, is brought in the right position for the light to fall on the corresponding phototube, and fixed there.

The slitholder assembly as a whole is interchangeable, and it can be replaced by similar assemblies or by a photographic equipment which makes it possible to register the entire spectrum. Normal 35 mm. film or bent plates can be used for photographs. The slitholder assembly *K* can be moved along the Rowland circle by the micrometer *U* and adjusted to its place by an optical arrangement. It consists of a reticule which should coincide with a certain visible line of the iron spectrum, and which is observed by a microscope *T* with a magnification of 100 times.

By this arrangement with interchangeable slitholders it is possible to analyze an arbitrary combination of nine elements with each slitholder assembly, with the same photomultipliers and with a minimum of adjustments at their exchange. Many combinations of elements to be analyzed are often demanded by industries, as they have to handle a variety of different samples of irons, bronze metals, light metals, minerals, etc. The electrical equipment is made in the conventional manner, giving an automatic and quick result. The units are placed in separate amplifier panels of a receiving set, and connected electrically to the spectrograph unit with screened cables. Generally, the electrical receiving system and the light-source feeding unit are placed close to the spectrograph, but the location is arbitrary as there are no other connections but cables.

The spectrograph equipment is at present under development, in collaboration between Mr. E. Aulin, Svenska Aktiebolaget Gasaccumulator, Mr. G. Carlsson, the Institute of Metallography, and the author, Optics Laboratory of the Royal Institute of Technology.

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SUMMARY

Le spectrographe comprend un réseau concave fabriqué sur la petite machine de Siegbahn. Ses dimensions sont 50 × 80 mm., la distance des traits 17,400 A, le rayon de courbure 1·5 mm. La lumière est concentrée dans l'un des spectres du 1er ordre. Les charactéristiques essentielles sont que le réseau est placé en bas de l'appareil et que la lumière provenant de l'étincelle ou de l'arc est refléché par un miroir vers la fente d'entrée, le faisceau étant d'abord horizontal, puis sensiblement vertical.

De cette façon l'axe de la source lumineuse est généralement vertical et aucune matière évaporée ne peut penetrer dans l'appareil.

Les récepteurs sont de 2 sortes : un chassis photographique ou un ensemble photoamplificateurs. On peut les interchanger facilement. Ils sont placés à la partie supérieure de l'appareil, en contact avec le cercle de Rowland qui est alors sensiblement horizontal. Les multiplicateurs sont precédés de fentes fixés correspondant aux divers elements. Les intensitiés lumineuses et partout les proportions des divers éléments dans le specimen sont mesurées par les variations de tension aux bornes de condensateurs reliés aux multiplicateurs. L'analyse est automatique. Le spectrographe est placé au centre de l'appareil et est accompagné du dispositif d'alimentation de la source d'un côté et de l'amplificateur analyseur de l'autre côté. De ce fait l'appareil occupe le minimum de surface de sol.

The spectrograph includes a concave grating ruled in the small Siegbahn apparatus with an area of 50 × 80 mm., spacing 17,400 A, radius of curvature 1.5 metres. The grating is "blazed" to give the maximum intensity in the used first order of one side. Its essential features are, that the grating is mounted at the bottom of the apparatus, and that the light from the spark or arc source is reflected on the entrance slit by a mirror, changing the light path from horizontal to nearly vertical. In this way the axis of the light source is, in the general, vertical, and no material sputtered from it can enter the spectrograph.

The receivers of the spectrograph are of two kinds : a photographic casette, or one of more units with photomultipliers. They are easily interchangeable, forming the top of the spectrograph and with the focusing circle lying roughly horizontal.

The photomultiplier units are provided with slits fixed once for all for the different elements. The light intensities, and, accordingly, the contents of the different elements in a specimen, are measured by voltage variations of condensers connected to the phototubes. The analysis is performed automatically.

The spectrograph unit forms the center of the whole arrangement, and it is surrounded by the light-source feeding unit on one side and the amplifier-analyzer set on the other. On account of this construction it takes a minimum of floor space.

9. Diffraction Gratings and the Plane Mirror: Some New Mountings

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Generally the spectroscopic resolving power of a diffraction grating can be written as the product of the total number of ruled lines N and the order of spectrum m. Thus:

$$R = \frac{\lambda}{d\lambda} = mN$$

These two quantities are, however, not independent of each other, their product $m\ N$ being limited by the ruled width W of the grating. Thus:

$$W = \sigma \cdot N$$

$$\frac{m\lambda}{\sigma} = \sin\alpha + \sin\beta,$$

where σ = line spacing or grating constant,
α = angle of incidence,
β = angle of diffraction.

This gives:

$$R = mN = \frac{W}{\lambda}(\sin\alpha + \sin\beta).$$

The maximum resolving power of the grating for light of the wavelength λ will thus be $2W/\lambda$. It is independent of the total number of lines and the grating constant[1].

The possibility of increasing W depends principally on the magnitude of σ. In ordinary gratings σ is of the order of dimension 10^4 A.U., in Woods Echelette gratings $\sim 10^5$ A.U., in Harrison's Echelle gratings $\sim 5 \cdot 10^6$ A.U. and in Michelson's Echelon interferometer $5 \cdot 10^7$ A.U. The orders of the spectra produced by these gratings increase generally in proportion to their grating constants

σ. It is very difficult to increase the width W of ordinary gratings, and especially of concave gratings. It is also difficult to increase the width of the Echelon grating composed of flat plates but, according to recent investigations[2], the echelle-echelette types of grating seem to be very promising in this respect.

However, a simple way of increasing the resolving power of already existing gratings suggests itself. In some prism-spectrographs the light beam passes successively through a number of prisms, the dispersion and spectral resolution increasing with every passage. For the same purpose a slightly different method is applied in the Littrow mounting of a prism. The light dispersed by the prism is reflected by a mirror, and after being again dispersed by the prism, its spectrum is focussed near the entrance slit. One prism thus disperses twice. An investigation of the corresponding relations for diffraction gratings shows that a combination of a grating and a mirror is appropriate and gives rise to some new grating mountings of different qualities as regards resolving power, dispersion, compactness and brilliancy. The principle, here applied, is especially applicable to blazed gratings, where a great part of the diffracted light is concentrated in the spectrum of one particular order. As a matter of fact, this investigation arose from proposals set forth some time ago by one of the writers (E. H.) in a discussion about how to make use of this blaze effect of modern gratings to gain highest brilliancy and resolution in the spectrum. It is published in *Arkiv for Fysik*[3] and some parts of it are reproduced here.

A mirror is placed in the diffracted beam from a grating reflecting the light back for a second diffraction. The spectral resolution can be expressed as the difference in optical path (measured in wavelength units) between the limiting rays of the beam. The mirror must therefore reflect the beam so that this difference is greater than it would be without using a mirror. It is even conceivable that a fraction of the beam will be diffracted so as to pass repeatedly between the grating and the mirror with increasing resolution and dispersion. The spectra produced in this way will here be termed primary, secondary spectra, etc., according to the number of diffractions. To what extent the method of double or multiple diffraction of light may increase the spectroscopic resolution depends greatly upon the optical qualities of the grating and the mirror. It will, however, be realized immediately that brilliancy may be gained by operating the grating repeatedly in an order of blaze, instead of operating it once in the corresponding higher order of the spectrum. The high orders of spectrum are generally also more troubled by ghosts due to imperfections in the ruling process.

§ 1. The Plane Grating and the Mirror

Neglecting terms of the third and higher degree in the grating formulae we have :

$$\frac{m\lambda}{\sigma} = \sin\alpha + \sin\beta \tag{1}$$

$$\frac{\cos^2\alpha}{a} + \frac{\cos^2\beta}{b} - \frac{\cos\alpha}{\rho} - \frac{\cos\beta}{\rho} = 0, \tag{2}$$

where a is the distance grating—slit,
b is the distance grating—image,
ρ is the radius of curvature of the grating.

These relations hold for the plane grating $(\rho = \infty)$ as well as for the concave grating.

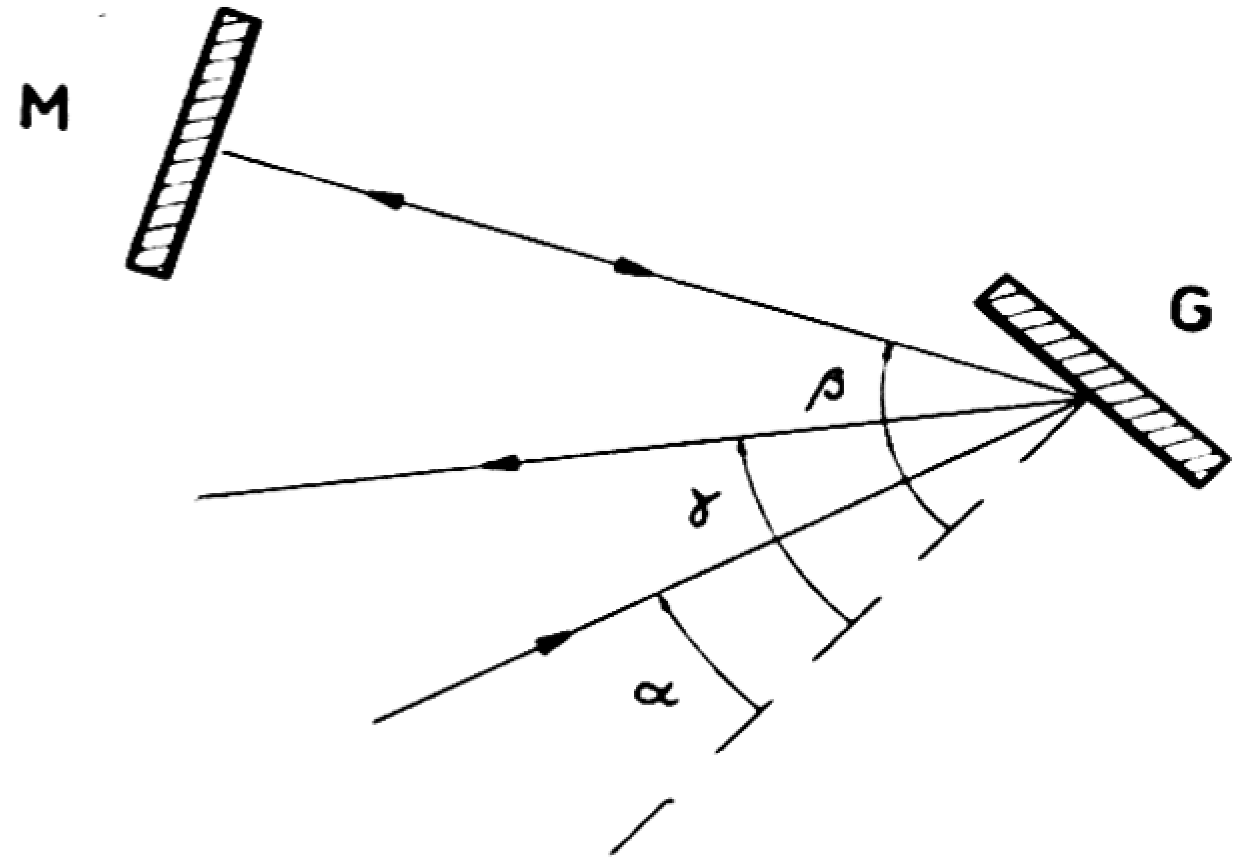

FIG. 9.1. Diagram relating to expressions for plane grating and mirror.

In Fig. 9.1 G is a plane grating and M a plane mirror. A parallel beam of light is incident at the angle α. A part of it of wavelength λ will be diffracted by the grating at the angle β and in the order p. This beam is reflected normally by the mirror, and is once more diffracted. Part of it will now be diffracted at the angle γ (its order being increased by q) and will form a final image after focussing. Part of the light will be spread into spectra of other orders. In order to deduce an expression for the resolution and dispersion of the final secondary spectrum of the order $p+q$ we consider the passage of the light in two stages.

slit→grating→mirror mirror→grating→final image

$$\frac{p\lambda}{\sigma} = \sin\alpha + \sin\beta \qquad \frac{q\lambda}{\sigma} = \sin\beta + \sin\gamma.$$

Noting that the beam diffracted at the angle $\beta + d\beta$ is reflected from the mirror at the angle $\beta - d\beta$, a differentiation of the above equations gives :

$$\frac{p}{\sigma}d\lambda = \cos\beta d\beta \quad \text{and} \quad \frac{q}{\sigma}d\lambda = -\cos\beta d\beta + \cos\gamma d\gamma.$$

Consequently the angular dispersion of light emitted from a slit (α const.) is

$$\frac{d\gamma}{d\lambda} = \frac{p+q}{\sigma} \cdot \frac{1}{\cos\gamma} \quad . \tag{3}$$

As the spectral resolution can be expressed as a product of the linear beam aperture and the angular dispersion we will have

$$R = W \cos\gamma \cdot \frac{p+q}{\sigma} \cdot \frac{1}{\cos\gamma} = \frac{p+q}{\sigma} \cdot W = \frac{\sin\alpha + 2\sin\beta + \sin\gamma}{\lambda} \cdot W \tag{4}$$

The same expression may be obtained by considering the path differences between the limiting rays of the diffracted beam. Thus we find $R_{\max} = \frac{4W}{\lambda}$, *i.e.* twice the value obtained without a mirror. Analogous expressions for the dispersion and resolution can easily be derived for tertiary and higher types of spectra, *e.g.* $R_{\max} = \frac{6W}{\lambda}$ for tertiary spectrum.

We have considered the following three cases of grating-mirror mounting :

(a) $\alpha = 0$, β variable, $\gamma \approx 0$ (Fig. 9.2a)
(b) $\alpha \approx \gamma$ variable, $\beta = 0$ (Fig. 9.2b)
(c) $\alpha = \beta \approx \gamma$ (Fig. 9.2c)

In all these cases the spectrograph is built according to the principle of autocollimation ($\alpha \approx \gamma$), *i.e.* the secondary spectrum is received near the slit. The mirror is mounted on an arm rotatable around a vertical axis in the centre line of the grating, thus allowing different regions of the spectrum to be selected. In the case (c) the mirror has been omitted, and instead the flat side of the plane-convex lens toward the grating has been silvered. The degree of silvering can easily be calculated. It depends on whether maximum intensity is desired at the secondary or tertiary spectra, and so forth.

(a) The first alternative with $\alpha = 0$, $\gamma \approx 0$ and β variable means that $p = q = m$ and thus the final order $2m$. The dispersion (Eq. 3) is $2m/\sigma$, which is its minimum value. The resolution (Eq. 4) is $\frac{2mW}{\sigma} = 2mN$. The maximum obtainable order $2m$ in the secondary

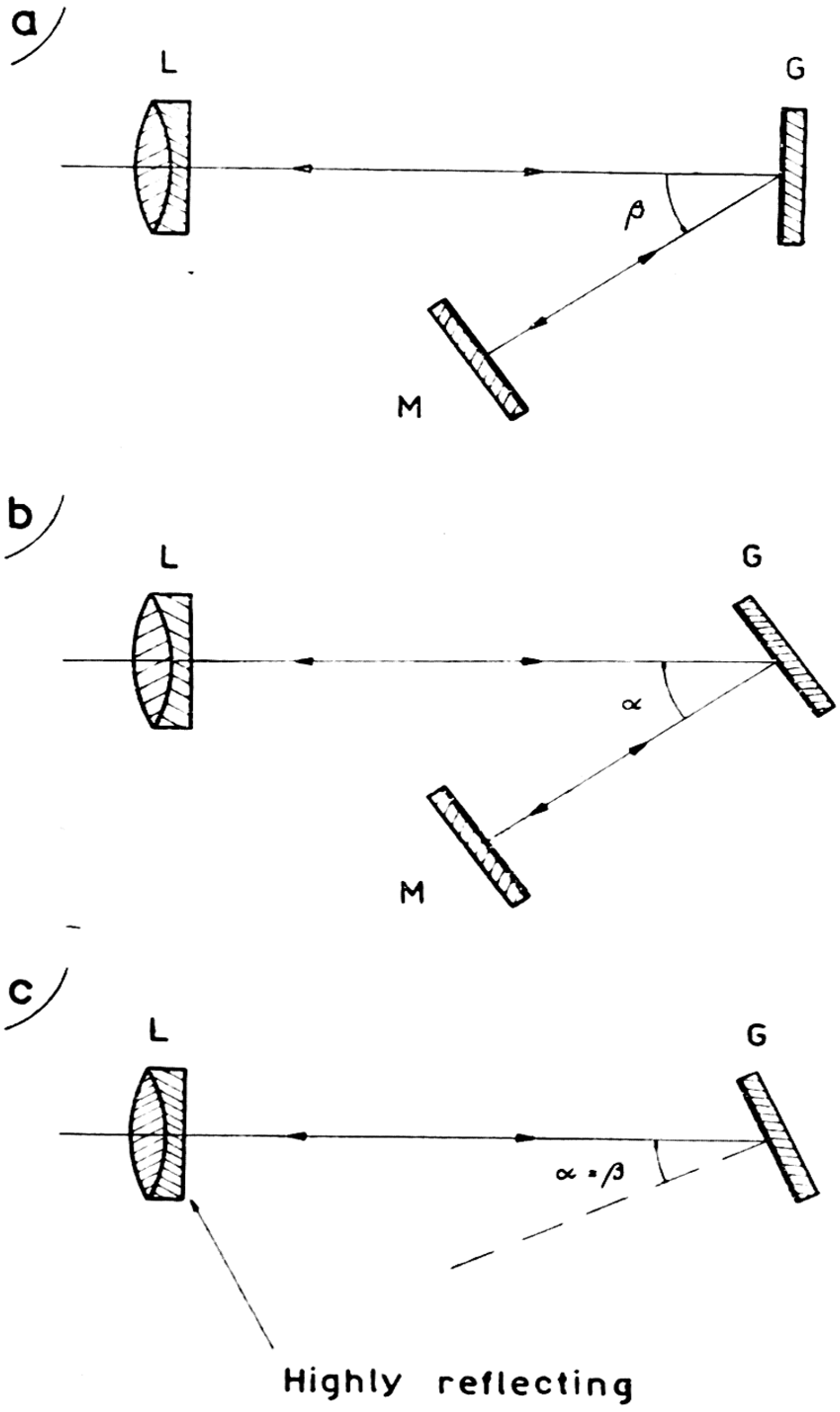

FIG. 9.2. Three cases of grating and plane mirror mountings (see also p. 105).

spectrum is determined by $2m \leqq \frac{2\sigma}{\lambda}$. This is the same limit, which holds for the maximum order in the Littrow mounting (with the dispersion $\frac{d\gamma}{d\lambda} = \frac{2m}{\sigma \cos_\gamma}$). In comparison with the Littrow mounting one can in this case neither gain in resolution nor in dispersion. The real difference between the two types of spectrum consists, however, in that the primary spectrum is produced by a grating acting directly in the order $2m$, while in the secondary spectrum the grating acts twice in the order m. This may entail a considerable gain of intensity in the second case, especially if the order m is distinguished by blaze.

It is clear that the available spectral range depends on the distance grating—mirror. It becomes more limited if this distance is increased. It is, moreover, clear that it is only for a still more limited spectral range that the high resolution is obtained. For rays not reflected normally by the mirror the whole grating is not illuminated at the second diffraction. These circumstances make it desirable that the distance grating—mirror should not be too great. On the other hand, the following difficulties may be noted.

While in the primary spectrum there is coincidence between spectral lines λ and λ' if

$$m\lambda = m'\lambda', \tag{5}$$

we get in our case

$$2m\lambda = [(s+r)^2 + (s-r)^2 tan^2\beta]^{\frac{1}{2}}.\lambda' \tag{6}$$

where β is the same angle as before and r is the order of the primary spectrum and $(r + s)$ is the order of the secondary spectrum of λ'. As r and s can be combined in several ways, one gets here a larger number of high-order lines than in the primary spectrum. If, however, the distance slit—grating exceeds a certain minimum value, defined by the dimensions of the grating and the mirror, all these disappear except the " normal " high-order lines, for which $r = s$ and consequently

$$m\lambda = r\lambda',$$

which relation is identical with Eq. (5). This minimum distance amounts (for an ordinary 3″ grating) to 25—50 cm.

(*b*) The second alternative with $\beta = 0$ and $\alpha \approx \gamma$ means that $p = q = m$, which gives the resolution $R = 2mN$ and dispersion $\frac{2m}{\sigma \cos_\gamma}$. The maximum obtainable order is $2m \leqq \frac{2\sigma}{\lambda}$. All these three characteristic quantities have obviously the same values as in the Littrow mounting, but as in the case (*a*) one can gain intensity especially if blazed gratings are used. (The spectrograms of Fig. 9.3 give some idea of this effect, even if the blaze of our grating is of minor strength.)

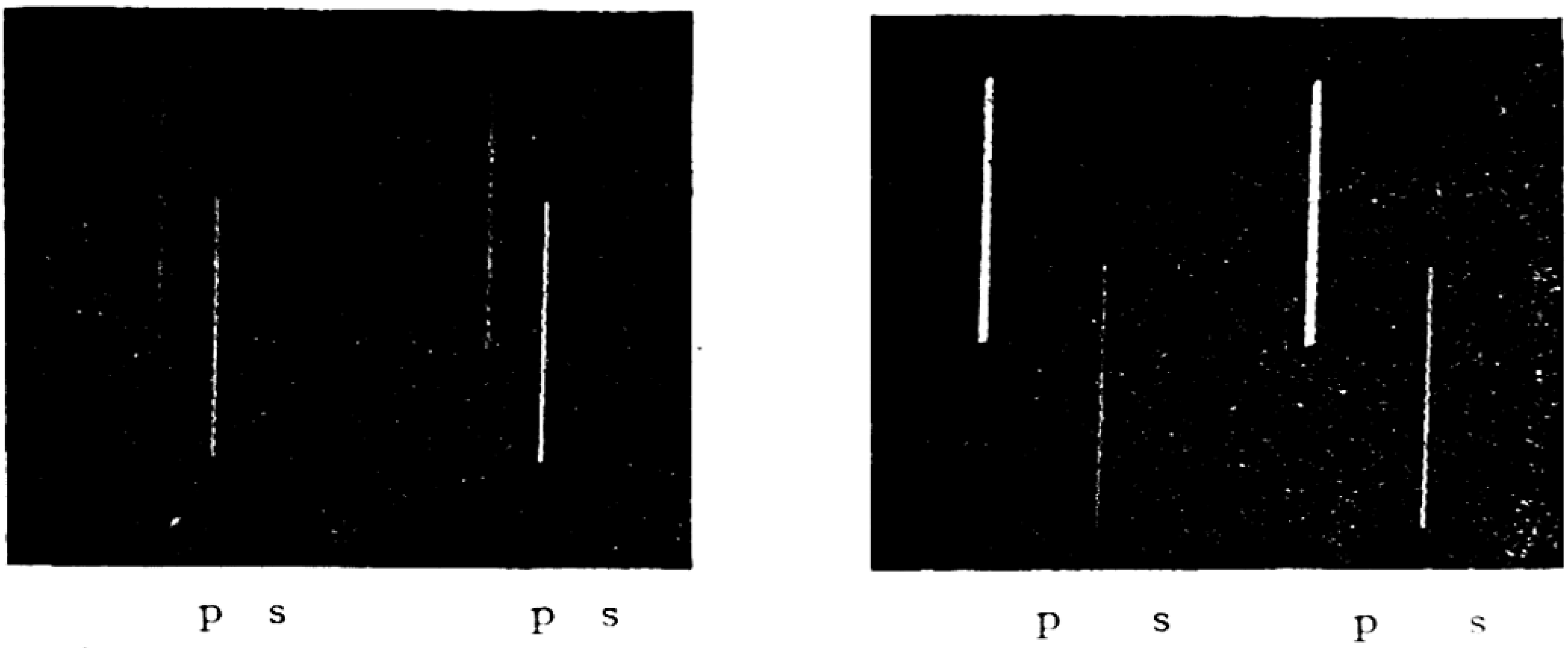

FIG. 9.3. Primary (p) and secondary (s) spectra of the yellow Hg-doublet (5770, 5791) in the 4th. order of the mounting of 1b, showing intensity effect produced by the blaze of the grating in one of its second orders, and (right) the lack of the effect in its other second order.

We have hitherto considered light of the order m which has been reflected normally by the mirror and has given a secondary spectrum of the order $2m$. It is, however, also conceivable that the primary spectrum of the order $(m-1)$ is obliquely reflected by the mirror, and at its second diffraction at the grating has its order increased by $(m+1)$ to $2m$. In the same way the order $2m$ can originate from $(m+1)+(m-1)$, $(m \pm 2)+(m \mp 2)$ and so on. It can be shown that all these final orders $2m$ arising from different order combinations coincide and have the same dispersion. Furthermore, they all coincide with the primary spectrum of the order $2m$, provided, of course, that the grating and the mirror are exactly parallel ($\beta = 0$). This method should be usable with Echelette gratings, where the spread of orders of the visible light is small and where some consecutive orders are often very brilliant. These coinciding spectra will, however, separate when the grating and the mirror are not exactly parallel.

For ordinary gratings giving large angle dispersion the whole grating will not be illuminated at the order combinations of these types $(m+1)+(m-1)$, and thus the purity of the spectrum decreases. It is therefore advisable in this case to withdraw the mirror so far from the grating that no oblique rays give any contributions to the secondary spectrum. As in § 1*a* these minimum distances can easily be estimated.

(*c*) $\alpha = \beta \approx \gamma$ gives $p = q = m$ and thus the final order $2m$. The resolution is $2mN$ and the maximum obtainable order $2m \leqq \frac{4\sigma}{\lambda}$. So here one gets a resolution twice as great as with the Littrow mounting. The dispersion in the secondary spectrum of the order $2m$ is $2m/\sigma\cos\gamma$. If the same order $2m$ can be obtained in the Littrow mounting its dispersion is $\frac{2m}{\sigma\sqrt{4\cos^2\gamma - 3}}$, *i.e.* greater than in the secondary spectrum. As in case (*a*) and in case (*b*), there is a gain in intensity, as well as in resolving power.

Here we get, for the coincidences between λ and λ', the following relation

$$2m\lambda = \frac{(s+r)^2 + (s-r)^2 \cdot tan^2 a}{s+r} \cdot \lambda', \tag{7}$$

where r and s have the same meaning as in case (*a*) above. Here too, of course, it holds that if the distance grating—mirror is not too small all high-order lines vanish except the " normal ", for which $r = s$ and $m\lambda = r\lambda'$.

The relations of coincidence in (*a*), (*b*) and (*c*) can easily be shown to be special cases of more general expressions valid for arbitrary α, β and γ. We have also considered the combinations of plane grating and concave or convex mirrors which might be used with non-parallel light, but have found these unsuitable.

§ 2. The Concave Grating and the Mirror.

With the combination of mirror and concave grating it is clear that it can only be useful to work on the Rowland circle or in parallel rays of light as in the Wadsworth mounting, because the errors of configuration will then be as small as possible. A study of the Rowland-circle case shows that a plane mirror does not increase the resolution of the secondary spectrum but that a concave or a convex mirror does, if it is placed with its centre of curvature in the primary line on the Rowland circle. The astigmatism will, however, be increased, and in addition to this only the secondary spectra of single lines can be obtained. We therefore find it impractible to combine grating and mirror in this way.

A simple and perfect solution of the problem is to work with a parallel beam of light between the grating and the plane mirror.

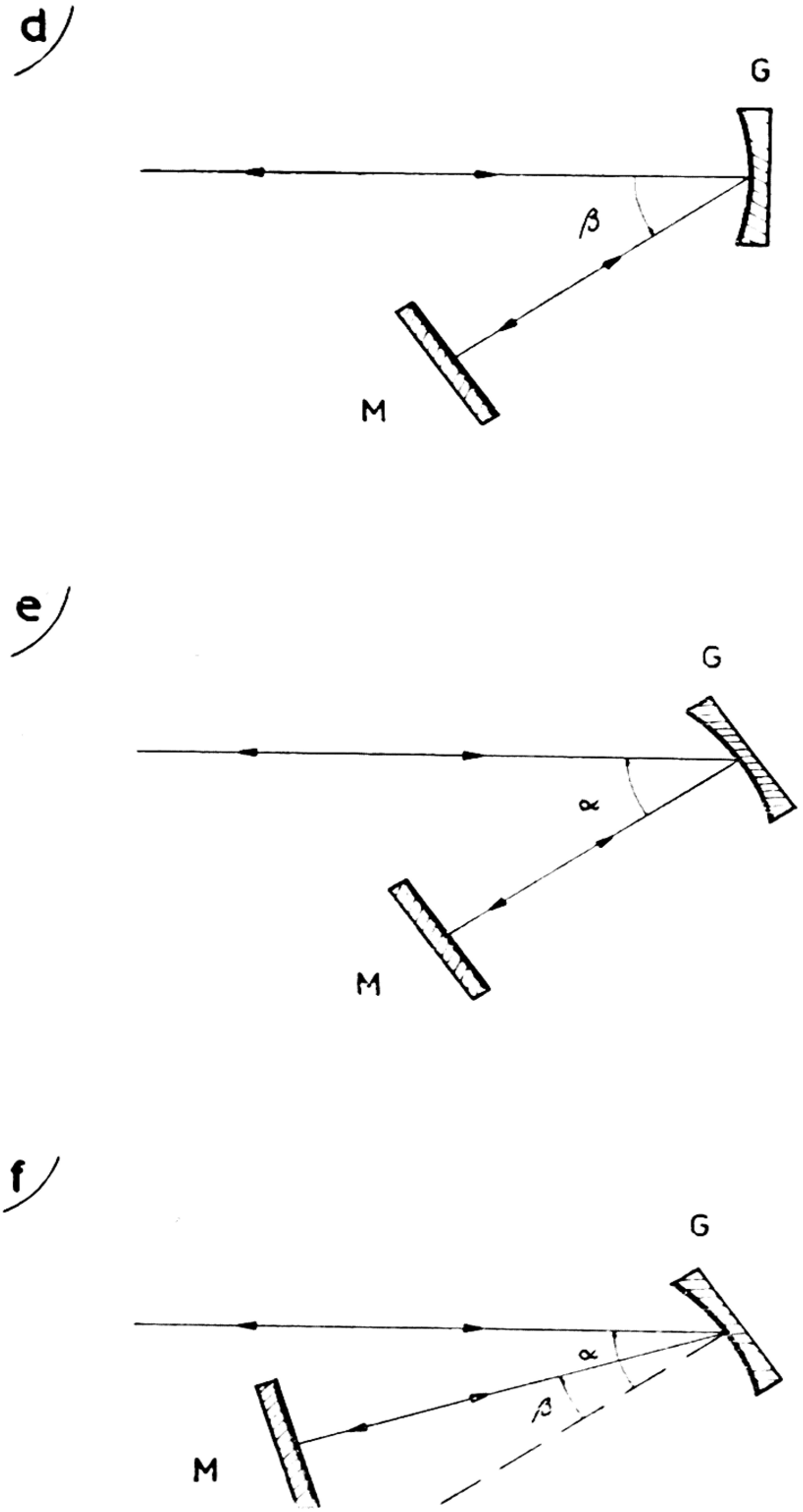

FIG. 9.3. Three cases of concave grating and mirror mountings.

The mirror is mounted as in § 1, so that it is rotatable around a vertical axis in the centre line of the grating. The relations (1) and (2) are valid and we have also here considered the cases

(*a*) $\alpha = 0$, β variable, $\gamma \approx 0$ (Fig. 9.2*d*)
(*b*) $\alpha \approx \gamma$, $\beta = 0$ (Fig. 9.2*e*)
(*c*) $\alpha = \beta \approx \gamma$ (Fig. 9.2*f*.)

The formulae for spectral resolution, the angular dispersion and the attainable orders are in all cases the same as those given in § 1. The comparisons there made with the Littrow mounting have here their counterpart in comparisons with the Eagle mounting. The coincidences which appeared at the plane grating on account of oblique incidence at the mirror do not appear here because such spectra are focussed in the space between the slit and the grating.

(*a*) Here $\alpha = 0$, β variable and $\gamma \approx 0$. From Eq. (2) the distance between the grating and the slit for $b = \infty$, $\alpha = 0$ is given by

$$a = \frac{\rho}{1 + \cos\beta}. \tag{8}$$

Thus a increases from $\rho/2$ to ρ when λ increases (see Table I). The configuration is stigmatic because this mounting fulfils the conditions $b = \infty$, $\alpha = 0$ for the primary spectrum and analogously for the secondary spectrum. The mounting gives high spectral brilliancy.

The exact focal curve is rather complicated, but as an approximation one gets

$$a_1 = \frac{\rho\cos^2\gamma}{\cos\gamma + \cos\beta}, \tag{9}$$

where a_1 is the distance from the grating to the secondary spectral line at the angle γ from the normal.

This focal curve is obviously the same as that of the Wadsworth mounting. Indeed, a comparison with this latter mounting is very interesting. For the same angles one finds that order, resolution and dispersion are twice as large in our mounting as in the Wadsworth mounting, but that, as already mentioned, the focal curve is the same.

(*b*) The case $\beta = 0$, $\alpha \approx \gamma$ gives for the distance a from the slit to the grating,

$$a = \frac{\rho\cos^2\alpha}{1 + \cos\alpha} \tag{10}$$

Consequently, a decreases from $\rho/2$ to 0 when λ increases (see Table) . This grating mounting is very compact but the astigmatism is high, and it seems, moreover, to involve disturbing diffraction fringes in the spectrum.

(*c*) $\alpha=\beta\approx\gamma$. The distance slit-grating is

$$a=\frac{\rho}{2}\cos\alpha \tag{11}$$

which decreases from $\rho/2$ to 0 with increasing λ. This mounting, too, is compact. The astigmatism is considerably less than in the case *b*. We have here not worked with a semi-transparent mirror as in § 1*c*, but the angle β has been increased or decreased so much that the grating is not shaded by the mirror.

TABLE I

Distance slit-grating for a concave grating with $\rho=640$ cm. ('21) and $\sigma=12{,}500$Å (20,000 lines at the inch) corresponding to the cases in §§ 2a, 2b and 2c.

α, β	$2m\lambda$	Distance slit-grating $= a$		
		$\alpha=\gamma=0$, β var.	$\beta=0$, $\alpha=\gamma$var.	$\alpha=\beta=\gamma$, var.
0°	0	320 cm.	320 cm.	320 cm.
15°	6475	326	304	302
30°	12500	343	257	277
45°	17675	375	187	226
60°	21650	427	107	160
75°	24225	512	35	83
90°	25000	640	0	0

§ 3. Some Remarks on Methods of Using the Suggested Mountings

The advantage of the spectroscope mountings shown in Figure 2 are completely realised only with blazed diffraction gratings. With such gratings 60 to 80 per cent. of the light is diffracted into one order or into a few consecutive orders. Even with repeated diffractions in one order of blaze the intensity is greater than obtained with a single diffraction in a corresponding higher order. It is thus possible owing to the blaze effect to increase the spectroscopic resolving power without decreasing the intensity too much.

Our method is readily applied to the plane grating mounted in auto-collimation and it exhibits the valuable properties already described in § 1. Additional favourable properties are realized when this principle is applied to the concave grating as in § 2. Especially the stigmatic mounting of § 2*a* affords greater simplicity and compactness than the Eagle and the Wadsworth mountings. The stigmatic configuration makes our mounting suitable also for infrared spectroscopy, spectroheliographs, etc. Simple mechanical devices may coordinate the angle of diffraction β and the positions of the grating and the slit as required by Eq. (8). The plateholder occupies a fixed position forming a curve through the slit normal to the slit-grating axis. This automatic setting and operation of the spectrograph will be valuable especially when using electric registration methods such as photomultipliers and PbS-cells.

We have made preliminary tests of the grating-mirror mountings, here discussed, with ordinary plane and concave gratings exhibiting practically no blaze effect. We are at present repeating our work using Siegbahn gratings, which show a very strong blaze effect.

We also considered the possibility of using the instrument for crossed spectra obtained when the mirror is replaced by a Fabry-Perot étalon (to be used in transmitted or reflected light).

Applying the principle of repeated diffractions we are also preparing a very simple automatic plane grating mounting where the parallel beam of rays is rendered by by a concave mirror. This mounting is especially devised for electric registrations.

REFERENCES

[1] Harrison, G. R.: *J. Opt. Soc. Am.* **39,** 522 (1949).
[2] Harrison, G. R.: *J. Opt. Soc. Am.* **40,** 127 (1950).
[3] Hulthen, E. and Lind, E.: *Arkiv. for Fysik,* **2,** 253 (1950).

SOMMAIRE

SUMMARY

La forte concentration de lumière qui caracterise les réseaux taillés a l'aide de diamants profilés permet d'effectuer un montage autocollimateur où un miroir plan renvoie la lumière dans la direction initiale. Dans certains conditions on obtient après une deuxième diffraction une meilleure résolution et une meilleure dispersion que dans le faisceau primaire.

La méthode des diffractions multiples permettra d'améliorer la résolution si la qualité du réseau et celle du miroir le permettent. On voit dependent que la brillance pourra être augmentée à la condition d'utiliser plusiers fois le réseau dans l'ordre pour lequel il y a une concentration importante de lumière, au lieu de l'utiliser normalement dans un ordre plus élévé. Ces idées ont été appliqués au réseau avec autocollimation sans autres dispositifs particuliers.

L'application au réseau concave est plus difficile mais on peut réaliser ainsi de nouveaux montages à grande brillance.

Le montage comportant un réseau concave et un miroir plan qui produit un spectre stigmatique et lumineux peut être appliqué a l'astrophysique comme spectrohéliographie. De plus, un étalon de Pérot Fabry placé dans le faisceau de lumière parallèle diffractée par le réseau permet de produire simplement des spectres croisés.

Le miroir plan est ici superflu, puisque le spectre peut être formé à l'aide d'une lentille, ou par le réseau concave, après reflexion sur l'étalon de Pérot Fabry.

The strong "blaze," which appears from gratings ruled with shaped diamonds, where a great part of the diffracted light is concentrated into one order, makes it possible to place a plane mirror in the blaze-direction of the diffracted beam, reflecting it back to the grating for a second diffraction. Under certain conditions the secondary spectrum exhibits a higher degree of resolution and dispersion than the beam first diffracted.

To what extent the method of double or multiple diffractions of light may increase the spectroscopic resolution depends greatly on the optical qualities of the grating and the mirror. It will, however, be immediately realized that brilliance may be gained by operating the grating repeatedly in an order of blaze instead of operating it directly in the corresponding higher order of the spectrum.

These ideas have been applied to the plane grating in autocollimation without any special devices. Their application to the concave grating is more intricate but they give rise to some new grating mountings of great brilliance.

The stigmatic and brilliant spectrum produced by the concave grating and the plane mirror makes it well adapted to astrophysical investigations, e.g., as spectroheliograph. Further, a Fabry-Perot étalon, placed in the monochromatic and parallel beam of light, diffracted from the grating, forms an instrument for producing "crossed" spectra of great simplicity and effectiveness. The plane mirror is here superfluous, as the spectrum may be projected either directly by a lens or reflected perfectly by the Fabry-Perot étalon to the grating and by auto-collimation finally focussed near the slit.

DISCUSSION ON GRATINGS

Dr. L. A. Sayce: A new method of making plane diffraction gratings has been devised by Sir Thomas Merton[1] and is being developed at the National Physical Laboratory. The method consists of three main operations.

(1) Upon one half of a polished metal cylinder is cut a helix having a pitch equal to that of the required grating. The helix is impressed by means of a diamond tool using a suitably geared-down screw-cutting lathe of special construction. Periodic errors in the helix due to the gearing and lead-screw are of no consequence but the helix as a whole must be free from progressive errors in pitch.

(2) The helix is copied upon the other half of the cylinder in such a way as to eliminate its periodic errors. The corrected helix is impressed by a diamond guided from the original helix on the principle of the chasing lathe but using a guiding nut lined with strips of a soft elastic material such as cork.

(3) The corrected helix is coated with the solution of a suitable plastic which after hardening and annealing is removed from the cylinder as a thin pellicle and opened out with the rulings down upon a moist gelatine coated plate of glass. When the gelatine has dried through the pellicle this can be stripped off leaving the gelatine moulded into a plane grating which can be hardened and aluminised.

The third stage of "flattening" the helical ruling presents the greatest difficulty and we have gained proficiency in it by practising upon existing plane gratings since it is then easier to compare the replica with the original. Our first problem was to prepare optically flat layers of gelatine upon glass and then to find means of preparing a pellicle of a plastic material which would transfer a copy of the grating to the gelatine surface without distortion. The degree of success we have attained is best shown by interferometric comparison of the diffracted wave-fronts of the original and replica gratings since perfect replication would produce an exactly similar fringe pattern. Examples show that the error of replication is about half a green fringe in the first order and this standard is likely to improve as we gradually perfect the details of our technique. It is quite possible by this process to improve an existing grating that has been ruled upon an unflat surface. Having developed a replica method for flat gratings with which the copies can readily be compared the method can be applied with confidence to helical rulings.

We are now perfecting the production of the helical rulings and have already had success in making rulings free from periodic error at spacings of 2,000, 5,000 and 15,000 per inch. In this work we make great use of the moiré pattern obtained when a transparent replica is halved at right angles to the rulings and the two halves suitably superposed. The wavy moiré fringes given by a grating produced directly from a lathe-cut helix are in striking contrast to the straight fringes from a grating derived from a helix corrected by means of the elastic nut.

It is as yet too soon to predict the full scope of this new method of making diffraction gratings. We are hoping to apply it to the production of large echellette and echelle gratings and the facility by which an indefinite number of identical copies can be made from each master helix has important advantages to makers of spectroscopic equipment. The method is protected by patents but licences to use it can be obtained through the National Research and Development Corporation.

Reference

[1] *Proc. Roy. Soc., A*, Vol. 201, 1950, pp. 187—191.

Dr. E. Hulthen. Considering the refractive index μ of the medium in which the echelle grating is operating, its resolving power may be given by:

$$R = \frac{2\,W \sin a}{\lambda} . \mu$$

where a = angle of incidence and diffraction.

This expression immediately indicates a way to increase its resolving power by immersing the grating in a transparent substance of high refractive index.

The idea may be applied in different ways, either by using some suitable liquid or more likely by combining the echelle with a glass or quartz prism in optical contact with the grating surface. It might also be possible to rule the echelle directly on the prism.

PHASE CONTRAST MICROSCOPES

10. La microscopie en contraste de phase

Prof. F. SCANDONE
(Officine Galileo, Italy)

(*A summary of this paper only is available*)

ON rappelle brèvement les principes et les buts du contraste de phase, les characteristiques d'un microscope pour la biologie générale sont précisées. En conséquence, on passe en revue et l'on discute les différéntes réalisations en terminant par les appareils italiens.

On étudie particulièrement les travaux de recherches effectués en Italie au suject de l'association de la stéreoscopie et du contraste de phase, la réalisation du contraste de phase variable et l'on développe des considérations théoriques sur la microscopie interferentielle et par contraste de phase.

Briefly recalling the principles and purposes of Phase Microscopy, the ideal specifications for a phase microscope for general biological purposes are formulated.

Subsequently the solutions adopted by different makes are reviewed and finally the solutions developed in Italy are described and discussed.

Particular attention was given to the latest research developments of the Italian group concerning the association of stereoscopy with phase microscopy, the practical realization of variable contrast, as well as theoretical considerations on phase and interference microscopy.

11. Phase Contrast Microscopy of Surface Structures

F. W. CUCKOW
(Chester-Beatty Research Institute, Gt. Britain)

PHASE-CONTRAST microscopy is now a firmly established and highly successful method of working and research workers owe a great debt to Professor Zernike for his fascinating invention and for his perseverance in seeing that it was brought into production and so made available to research workers generally. Dr. Burch in this country led in our own advance and, by his expositions of the subject, gradually but I believe with some little difficulty, interested our own workers in the possibilities of the method. Messrs. Cooke, Troughton and Simms are to be congratulated on taking the subject up as soon as conditions permitted and it is very largely due to them that so many research workers in Britain now have phase-contrast equipment.

The early work in phase-contrast microscopy was directed to the biologist's normal microscope—the transmission type of instrument —in which normally invisible object detail was rendered visible in terms of its varying thickness or in terms of refractive index differences between object and background.

No attention appears to have been paid to the possible application of the method to the incident light microscopes used for examining the surfaces of opaque objects and this is perhaps rather surprising as one of the early applications of the phase-contrast method was to the examination of the " figure " of telescope mirrors which was essentially an examination of surface form on a macroscopic scale.

The author's own interest in the possibility of such an application arose indirectly from other microscopical work involving the electron microscope and it is perhaps interesting to follow the development of the application of phase-contrast to the incident light microscope in that way as it brings out the principles involved and provides a good illustration of the interplay of microscopical methods.

Electron Microscopy of Surface Structures

The surface structure of massive specimens cannot be examined in a normal transmission type of electron microscope and recourse is made to the " replica " technique by which a cast is made of the surface in a plastic material and the cast is examined in the electron microscope in place of the original specimen. The essential point is that the cast can be made as little as a few hundred Ångstrom units thick by appropriate techniques and is then more or less transparent to the electron beam according as it corresponds to an elevated or a depressed area of the specimen. It follows that the brightness of a point in the final image is a function of the elevation of the corresponding point in the parent specimen and the topography of the specimen may therefore be determined.

The normal aim of electron microscopy is the enhanced resolution which is associated with the very short effective wavelength of the high velocity electrons comprising the beam but an intercomparison of light and electron micrographs shows that this is not always the only gain.

For example, Figures 1 and 2 are respectively light and electron micrographs at the same magnification of the etched surface of an alloy steel. The light micrograph has been prepared under oil immersion on a normal metallurgical microscope and the electron micrograph has been prepared from a " Formvar " replica of the same specimen on an 80-Kilovolt electron microscope.

The pictures show marked differences. The gain in definition is obvious and is to be expected. The electron micrograph provides in addition a marked distinction between certain areas of the metal surface, one group appearing relatively dark against a much lighter background. No such clear cut differentiation into two types of area is to be seen in the light micrograph although an experienced metallographer recognises their presence from other more subtle effects.

The simple interpretation of the electron micrograph leads to the conclusion that two major metallurgical constituents are present in the specimen. One constituent etches more rapidly than the other so that its surface becomes lower than that of the general

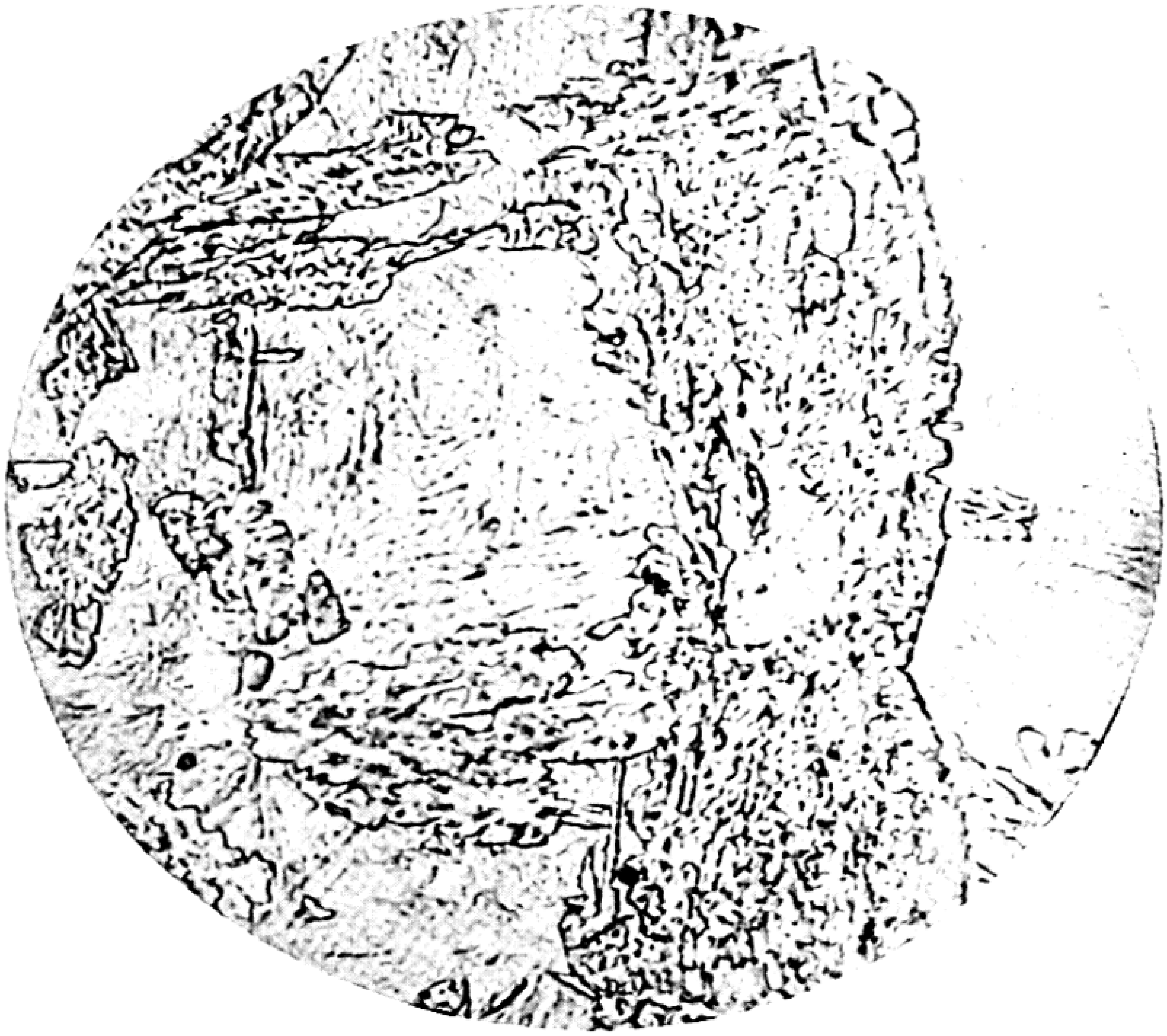

FIG. 11.1. Photomicrograph of alloy steel, mag. × 1,500.

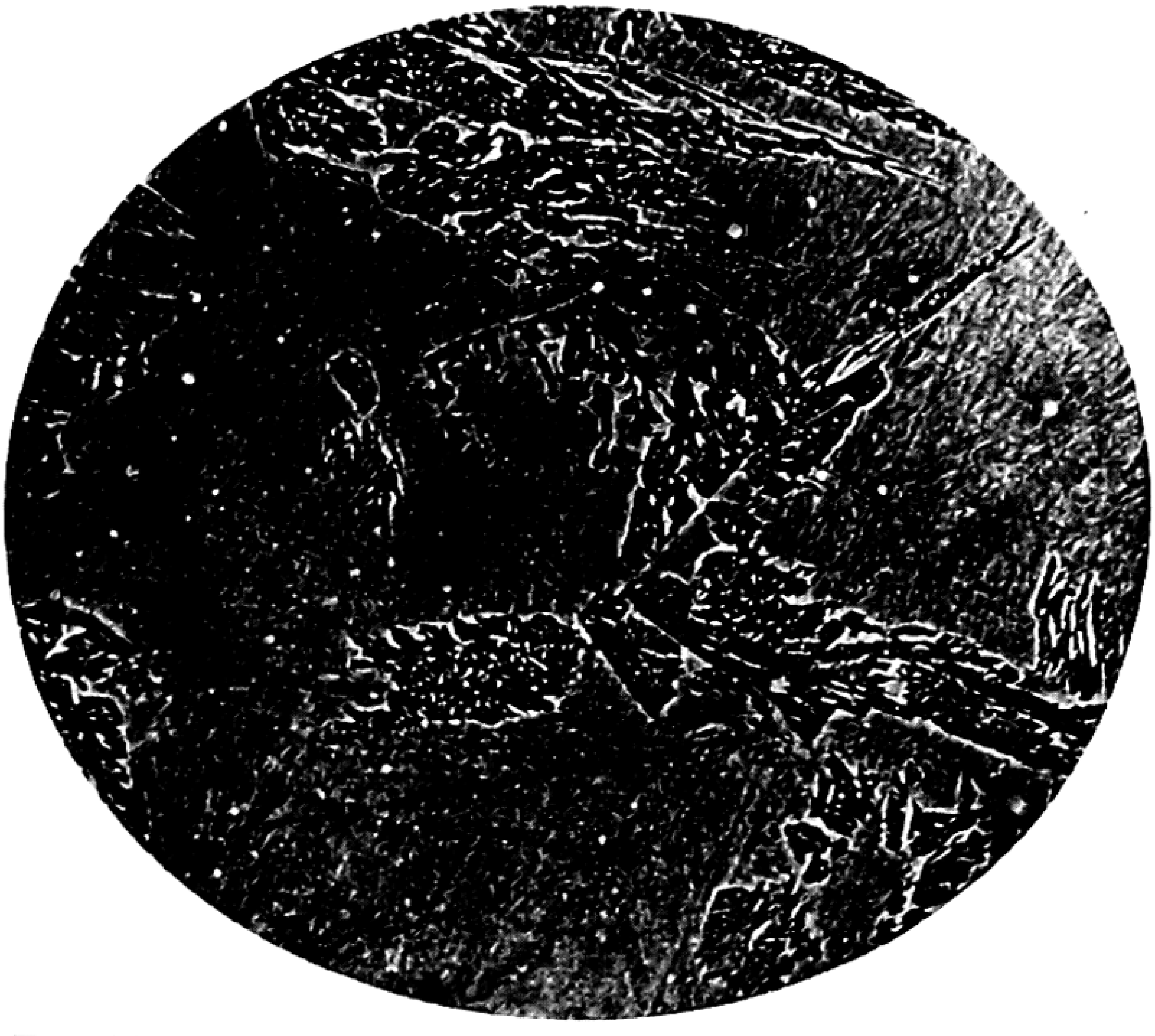

FIG. 11.2. Electron Micrograph of alloy steel, mag. × 1,500.

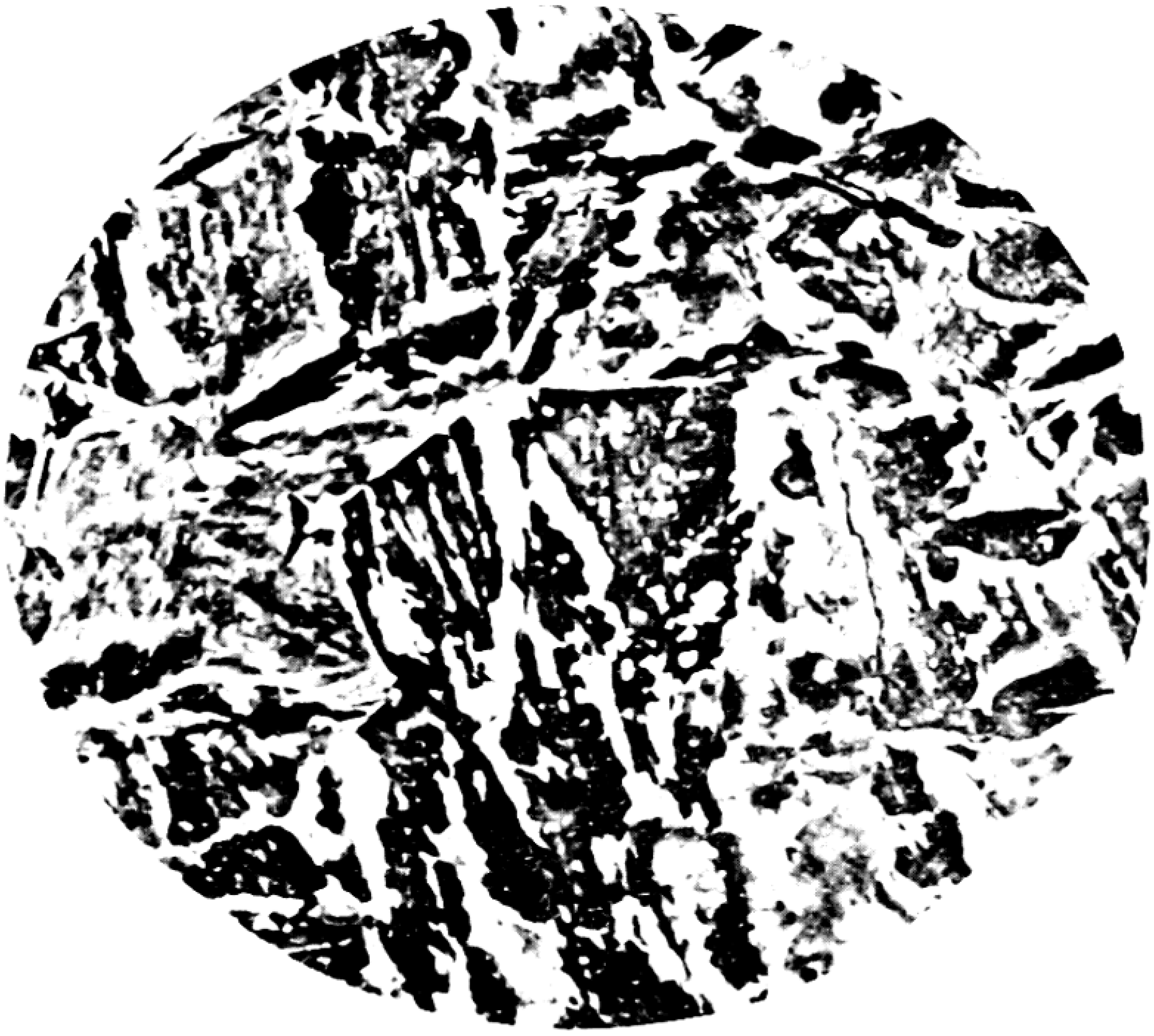

FIG. 11.4. Phase-contrast Photomicrograph of alloy steel, mag. × 1,500.

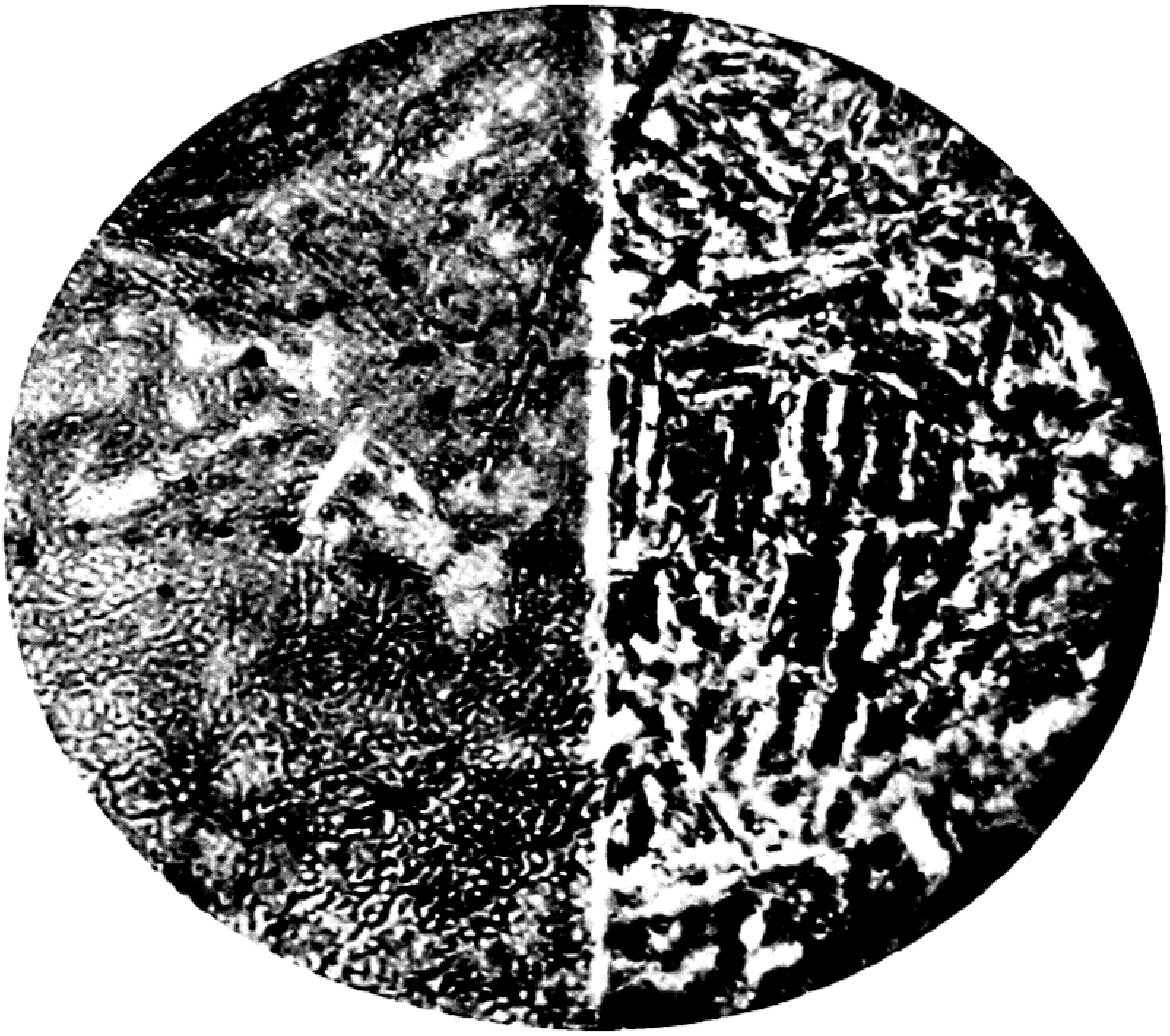

FIG. 11.5. Split-field comparison of normal and phase-contrast micrography of alloy steel, mag. × 1,500.

body of the specimen, and when a cast is made of the surface this depression leads to a thicker part of the replica and so to a darker area in the electron micrograph.

This advantage of the electron micrograph, in giving a high degree of contrast between the two major constituents, is therefore seen to be associated with characteristic *variations in level* in the surface of the specimen and this is a feature which the normal metallurgical microscope is quite incapable of rendering visible other than in terms of disturbances set up at the mutual boundaries of the constituents.

The conclusion is therefore drawn that we have gained not only in definition but also in visibility and this latter is a very desirable advantage.

Electron microscopy of surfaces is, however, as yet a very exacting technique and on a time basis compares very unfavourably with normal metallurgical microscopy in which a visible image can be presented to the observer within a few seconds of preparing the metal specimen. By contrast the electron microscopist must first prepare a replica and then photographically record an electron micrograph since the visible image on the fluorescent screen of the microscope seldom has sufficient contrast for direct visual work. Each of these steps consumes a considerable amount of time.

It would be possible to examine the replica directly and visually on a transmission type phase-contrast microscope. Such work is in fact illustrated in the first Zeiss phase-contrast microscope catalogue, but the delays and difficulties associated with replica formation remain.

The variations in surface level which have been demonstrated by the electron microscope must themselves impose phase changes in reflected light during examination on a metallurgical microscope on account of the variations in path length corresponding to various parts of the object. The advantages of depth discrimination which were demonstrated in the electron micrograph would therefore be secured on an optical instrument if phase-contrast methods were applicable to the incident light microscope, so that the phase differences corresponding to varying surfaces levels were converted into brightness differences in the visible image.

This was in fact done in the author's laboratory and in three other laboratories, all working quite independently of each other and with differing aims in view, some three years ago. [1] [2] [3] [4] [5] [6]

Direct Phase-contrast Microscopy of Surface Structures

In the author's work use has been made of normal phase-contrast objectives intended for transmission microscopes and attention has been confined to high power oil-immersion objectives for reasons which will appear later.

The annular phase change ring is formed in such objectives on a lens face quite close to the back focal plane. It follows that an identical image of the ring can be formed in its own plane if a mirror is placed in the normal object position just below the objective. Suitable orientation of the mirror will cause the ring and its image to coincide exactly.

If then the objective is used in a metallurgical microscope with a perfect mirror specimen and light passing through the objective to the mirror is confined to the area of the annulus, all the light returning after reflection at the mirror must pass through the phase change ring since the ring and its image are coincident.

Substitution of a normal metallurgical specimen for the mirror gives rise to diffracted light owing to its less perfect surface and this light passes through the whole aperture of the objective lens.

We then have phase-contrast conditions in which the direct light leaving a point on the object passes through the objective and the annular phase change ring in the form of a hollow cone, while light diffracted at the object is free to pass through any part of the objective aperture.

The optical system used to achieve this is shown diagrammatically in Fig. 3.

Other workers have avoided sending the incoming light through the phase change ring as this is necessarily absorbent and a large part of the available light is wasted. This is not in one way serious since a compact mercury source is still more than adequate even at high powers but the ring may possibly reflect light back into the viewing system and so reduce the contrast obtainable.

Such back reflections as do arise cause no difficulty in the case of both the Cooke and the Zeiss oil immersion phase-contrast objectives each of which has been used in the manner described above, but serious difficulties are experienced with the 4 mm. phase-contrast objectives if employed in this unusual manner on account of back reflections which the computer would not of course have been required to consider in a lens intended for transmission work.

Application of the Method

An experimental microscope constructed in the manner described above has been tested on a number of metallurgical specimens.

It was pointed out earlier that Figs. 1 and 2 were respectively light and electron micrographs from the same steel alloy specimen. Fig. 4 is a comparable micrograph from the phase-contrast incident light microscope. The degree of etching of the metal specimen has been maintained substantially constant for the three micrographs while the contrast has been photographically enhanced in the case of the electron micrograph and reduced in the case of the phase-contrast micrograph.

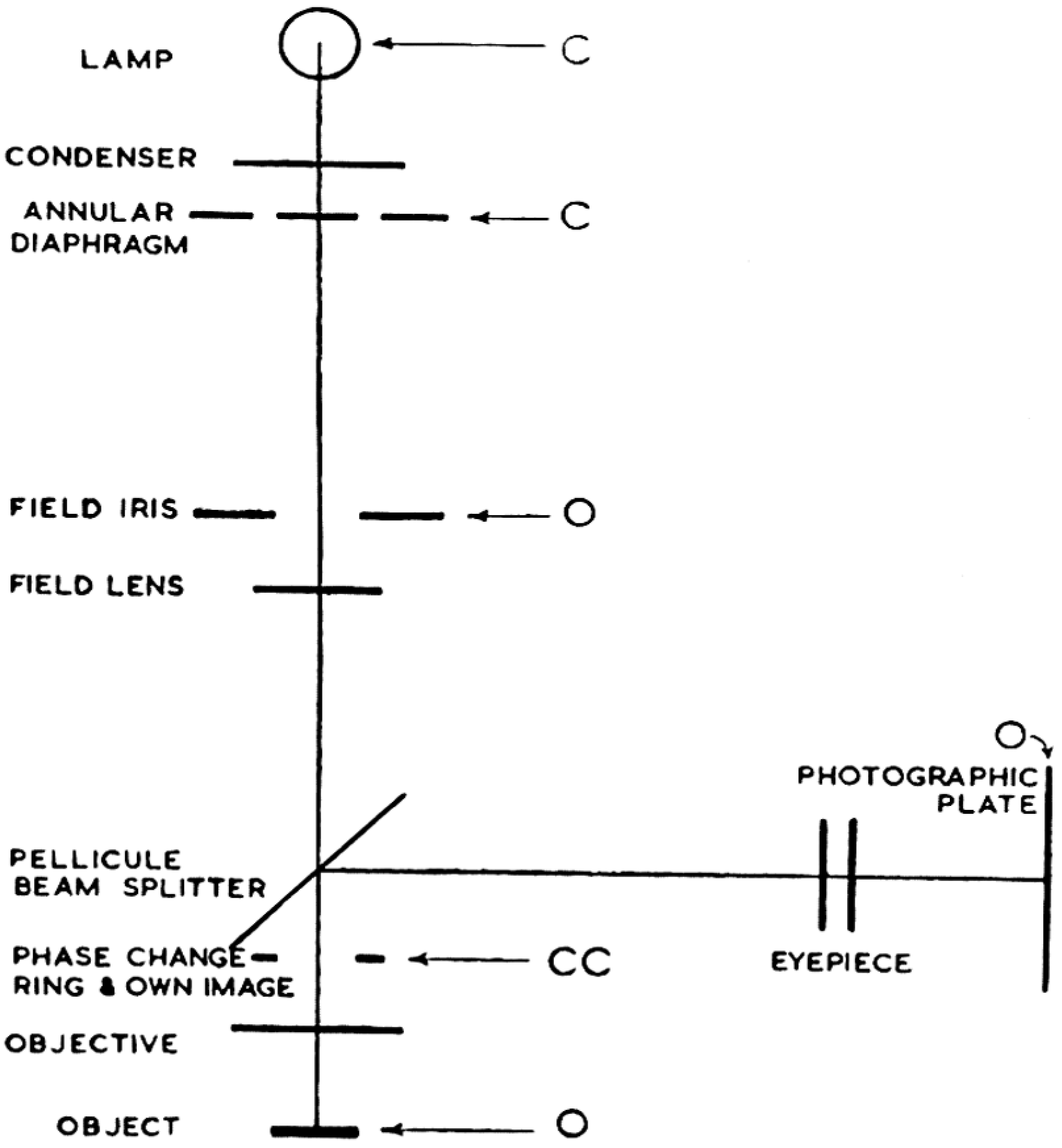

FIG. 11.3. Phase-contrast incident light Microscope (Diagrammatic). Planes marked " C " are mutually conjugate, as are planes marked " O ."

Intercomparison of the micrographs shows that valuable contrast effects, obtained in the electron micrography and associated with variations in surface level, can be obtained even more markedly in the phase-contrast incident-light microscope which offers moreover the advantages of direct visual observation of specimens and of unrestricted lateral adjustment of the specimen which enables the whole of its surface to be examined very quickly.

A survey of the usefulness of the method has been made by the author [5] and greatly extended by McClean [7] to whose papers reference may be made for further illustrative micrographs.

The extreme sensitivity of the method to variations in surface level is illustrated by the micrographs in Figs. 1, 2 and 4. The variations in surface level presented by the specimen lie within a range of 250 A.U. and yet they lead to extremely high contrast in the phase-contrast photomicrograph. No attempt has been made by the author to determine the depth discrimination threshold, but it must clearly be a very small fraction only of 250 A.U. Sensitivities of this order are likely to make the method of importance in the appraisal of higher degrees of surface finish, a matter of great importance in the engineering industry.

At first sight the method appears inapplicable to objects which are more or less transparent and so give poor surface reflections or perhaps confusing reflections from levels below the surface as might arise with opalescent materials. These difficulties can be readily overcome by evaporating reflecting layers on the surface. Such reflecting layers can increase the surface reflection and suppress confusing internal reflections but still leave the topography of the surface substantially unchanged as is shown by Tolansky's elegant experiments in multiple beam interferometry.[8]

It is a great advantage in examining a specimen to be able to use a number of microscopical methods in quick succession on exactly the same area of the specimen so that the best method may be quickly determined.

It is not difficult to devise an incident light microscope which will present an enlarged image of a single field of the specimen divided into two parts. One part is seen under normal incident light conditions while the other part is seen under phase-contrast conditions so that any specimen area of interest may be seen by either method by a simple translation of the object. Fig. 5 shows a micrograph prepared on such a microscope made by the author.[5] The division of the field into two parts may be achieved in a number of ways. In the present case polaroid filters were used. The addition of a further polaroid filter at the eyepiece would then convert the instrument into a polarising microscope so that normal, phase-contrast and polarisation microscopy could be used in rapid succession.

Interpretation of the Micrographs

There are perhaps two lines of approach to the question of interpretation.

Many workers in examining a solid surface would be satisfied to observe the image through the microscope and base their deductions on its microstructure upon the general appearance in association with experience of similar specimens and knowledge of the treatment to which the specimen had been subjected. No direct attention would be given to the topography of the surface. In such a case, it will be sufficient if workers gradually build up experience with the phase-contrast incident light microscope on a wide range of specimens as was in fact done with the normal metallurgical microscope. Their interest in the phase-contrast microscope will lie simply in its ability to make visible features which were previously unseen.

Other workers may wish to obtain direct information on the surface topography and closer attention will then need to be paid to the mode of image formation in these new microscopes.

It is clear that elementary interpretation of the phase-contrast micrograph can be based directly on variations of surface level giving rise to proportionate variations in image brightness but more detailed interpretation must take account of the possibility of phase changes arising from causes other than variations in surface level. Phase changes of an unknown degree will take place at metallic reflection. Contrast might therefore arise from co-planar surfaces exhibiting differing phase changes at reflection. There is as yet not enough information available on such matters and both theoretical and practical work is required to put the matter on a quantitative basis. Further, the light reaching a specimen is commonly more or less polarized on account of reflectors in the optical system and it is probably necessary to study the interrelationship of phase-contrast and polarization effects before attempting anything other than a simple interpretation of the micrographs.

Some of the uncertainties may perhaps be avoided by depositing a thin reflecting but opaque layer of metal over a specimen prior to examination [5] as this would suppress the individual natures of the constituents but leave the topography unchanged so minimizing the factors which may give rise to phase differences.

A further factor affecting the application of the method in a quantitative manner is inherent in the objective lenses available, and in fact in the particular objective lens used for the work in question. The variation in path length through an optical system from any one object point to the corresponding image point is commonly held within the Rayleigh limit of $\lambda/4$, but such a phase variation is very large compared with the phase changes detectable by phase contrast methods and is in fact as large as the phase change deliberately introduced to produce the phase contrast effect.

Now the degree of contrast introduced by the phase contrast effect is a function of the phase difference between the direct and diffracted beams.

The direct beam all passes through the annular phase change ring and therefore passes through the system at a substantially uniform inclination to the axis. Assuming axial symmetry, therefore, all direct rays are subject to the same retardation and arrive at the image plane in phase with one another.

The diffracted light on the other hand passes through the system at the variety of inclinations to the axis up to the limits set by the aperture of the particular lens in use.

The resultant vibration in the image plane due to diffracted light is the sum of the vibrations received from all parts of objective and due allowance must be made for the distribution of light over the aperture and also for the phase retardation introduced by the system appropriate to the particular element of the aperture under consideration. The phase retardations will depend largely on the inclination of the rays to the axis but will be invariable in any one lens. On the other hand, the distribution of light over the objective aperture depends upon the nature of the specimen.

As a result, the degree of contrast in the final image depends not only on the phase differences introduced by the specimen but also on the nature of the specimen with particular reference to the distribution of light in the diffracted wave. This effect is, of course, common to both transmission and reflecting systems and may be minimized by the use of superior objective lens systems.

In this connection, it is interesting to note that interferograms produced in testing objective lenses sometimes show that a phase change of about $\lambda/4$ exists over a fairly narrow annular zone corresponding to an aperture of perhaps 0·5, while errors over the remainder of the aperture are quite small. Such a lens, which would normally be considered quite acceptable, might well give rise to appreciable phase-contrast effects.

If it were used with an annular condenser stop it would approximate quite closely to a normal phase-contrast objective and the similarity would become even more marked if an annular stop were used in the objective in such a way as to cut down the direct light without reducing the diffracted component.

Commercial Microscopes for Phase-Contrast Microscopy of Surfaces

As far as is known, the only phase-contrast incident light microscope on the market is that made by Messrs. Cooke, Troughton and Simms and described by Taylor.[6] It has achromatic objectives of the normal powers 10, 20, 40 and 95. The light is introduced to the microscope by a beam splitter placed between the objective and the annular phase change ring, the latter being formed on a separate piece of glass. Such a system is less wasteful of light than that used by the author and back reflection difficulties are minimized at the same time.

The condenser system has variable magnification so that the projected image of the annular condenser diaphragm may readily be brought to the same size as the phase-change ring of the particular objective in use. The microscope is very little more difficult to use than a normal metallurgical microscope.

Phase-contrast incident light microscopes have been made by other firms notably American Optical Co.[2] [4] and Watson and Co., but it appears that neither has been made available to research workers generally.

A most interesting parallel development is the interferometer microscope of Dyson,[9] but this also has not yet reached a commercial stage.

A further instrument of interest is the Zeiss-Linnik interferometer microscope. This is not well known although a single example is in Britain.

Each of these microscopes, as the name implies, divides the beam into two parts and subsequently re-unites them to give rise to interference. One part passes through or is reflected from the object and so becomes modified in phase, while the other serves as an unmodified comparison beam. The Linnik microscope uses two matched objectives, one focussed on the test specimen and the other on a plane comparison surface. Dyson's microscope on the other hand uses only one objective in conjunction with a most ingenious optical system to achieve the beam division and subsequent recombination.

Acknowledgments

Acknowledgments are made to the Iron and Steel Institute for their courtesy in permitting reproduction of the photomicrographs from their Journal.

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SOMMAIRE

La méthode de la microscopie par contraste de phase a été appliquée ces dernières années à l'examen de la structure des surfaces. L'histoire de cette méthode est rappelée et les relations avec d'autres méthodes microscopiques sont exposées. Il serait utile de poursuivre des travaux théoriques et pratiques dans certaines directions. On donne quelques détails concernant les appareils actuellement existants.

SUMMARY

The phase-contrast method of microscopy has been applied over the last few years to the examination of surface structures. The history of this method of working is traced and its connections with other microscopical methods are explored.

Further theoretical and practical work is required in certain indicated directions. Some details are given of phase-contrast incident light microscopes now available.

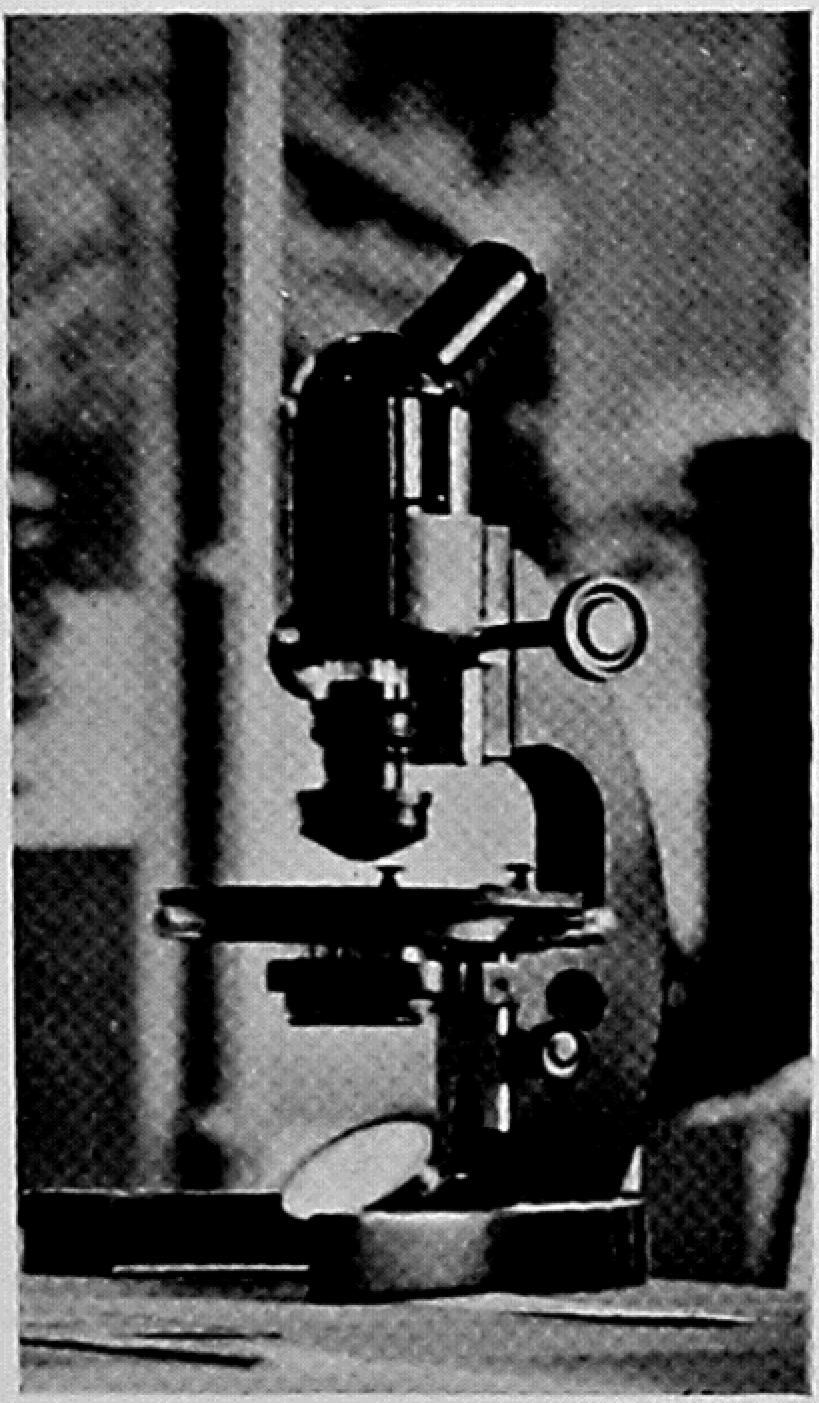

FIG. 12.2. Microscope à contraste de phase. Dispositif placé entre la préparation et l'objectif.

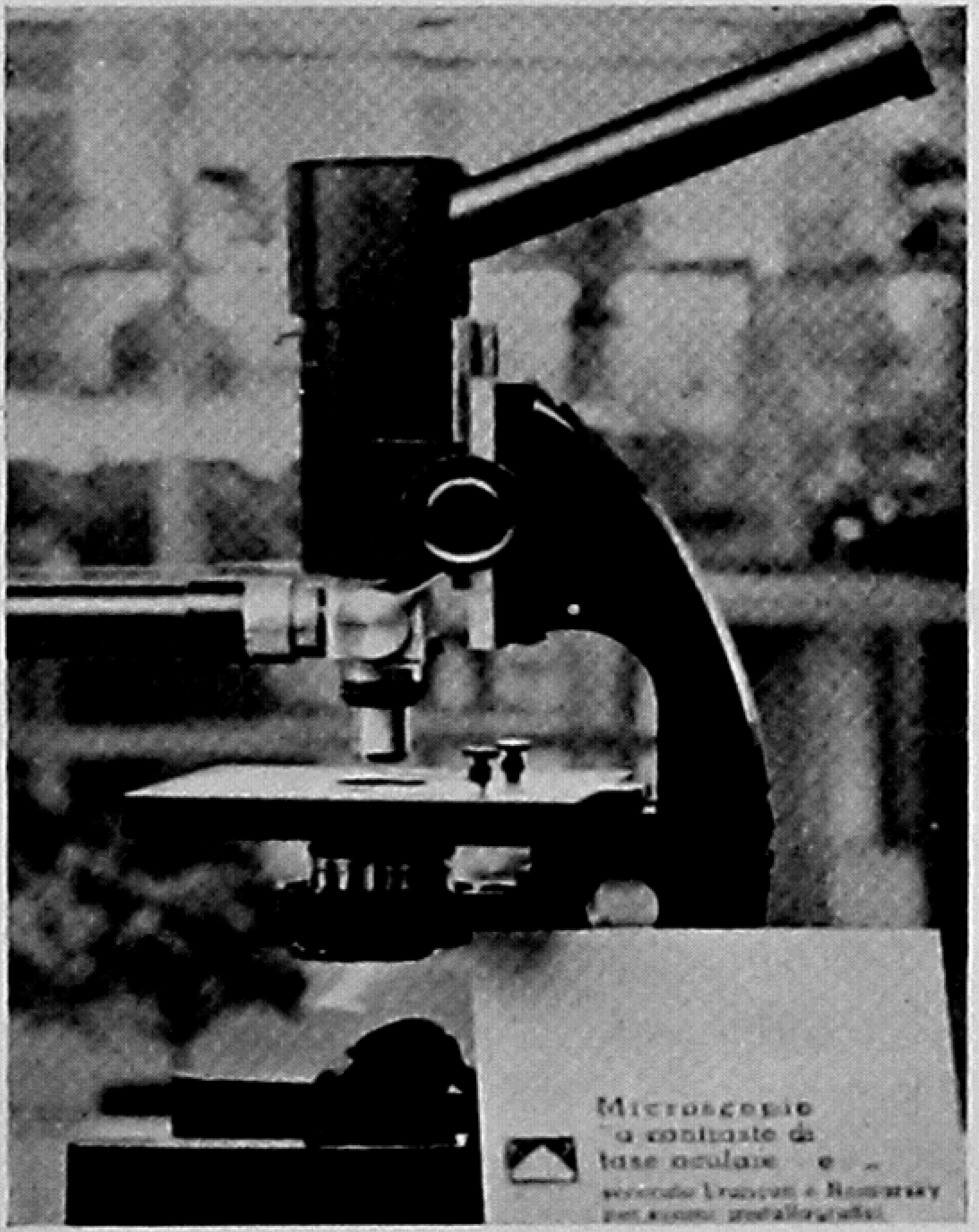

FIG. 12.4. Microscope à contraste de phase. Dispositif placé après l'oculaire, pour un objet réflechissant.

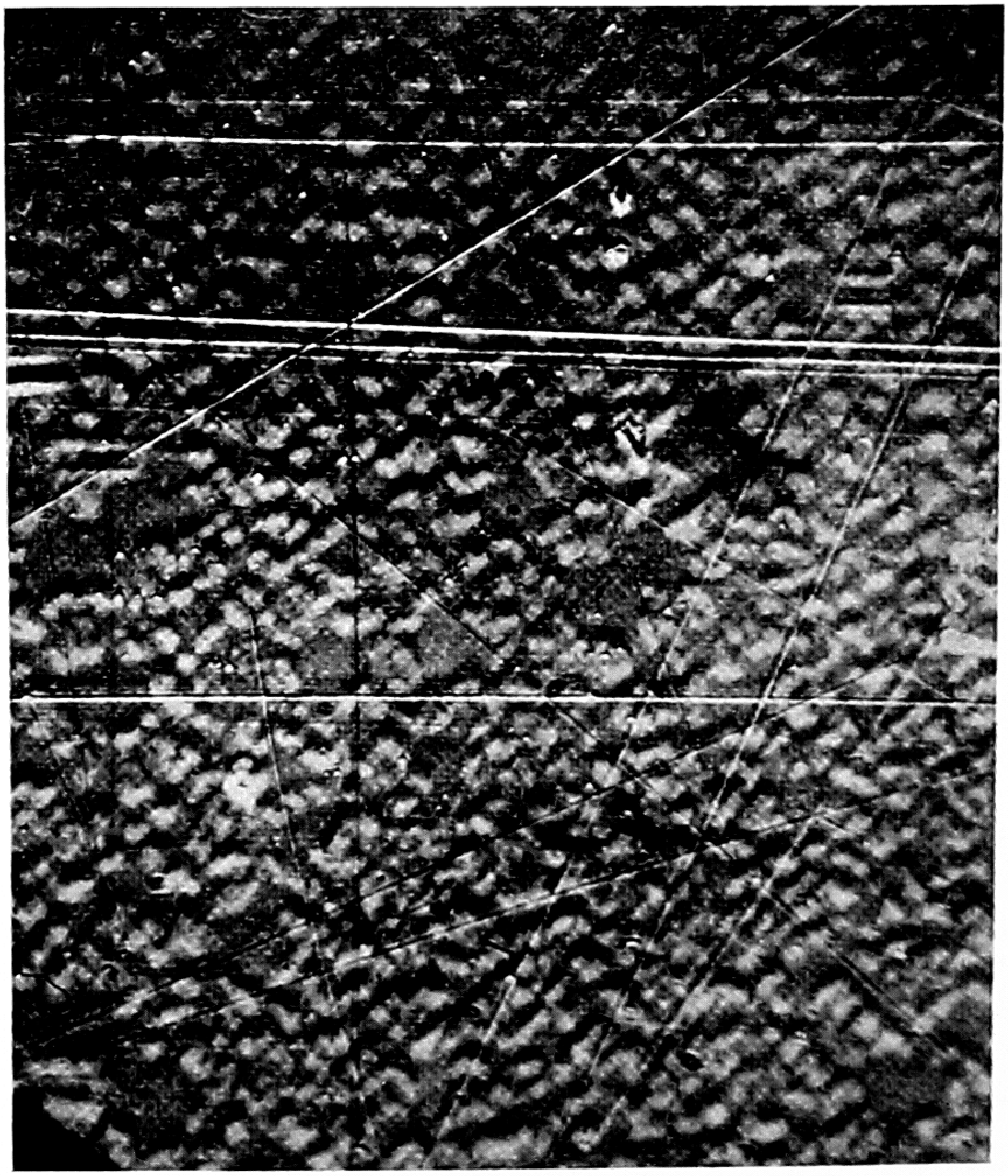

FIG. 12.5. L'aspect d'une lamelle couvre-objet.

12. Etude et réalisation du contraste de phase indépendant du microscope

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Cette étude a été entièrement réalisée avec la collaboration de M. G. Nomarski, attaché de recherches au Centre National de la Recherche Scientifique.

Dans les appareils que nous avons réalisés à l'Institut d'Optique de Paris, nous nous sommes efforcés d'utiliser le microscope ordinaire, sans changer ses éléments fondamentaux. La partie contraste de phase proprement dite est une partie indépendante qu'il suffit d'ajouter au microscope pour transformer l'appareil en microscope à contraste de phase.

Deux solutions sont possibles quant à la position du dispositif à contraste de phase. Le système peut être intercalé entre la préparation et l'objectif, ou bien placé après l'oculaire au moyen d'une rallonge. Le premier dispositif spécialement adapté pour être associé aux objectifs à immersion de forte ouverture numérique, possède une lame de phase annulaire. Le deuxième dispositif peut couvrir toute la gamme des grossissements et utilise une lame de phase linéaire.

1. Dispositif à contraste de phase placé entre la préparation et l'objectif

L'appareil est représenté schématiquement par la figure 12.1. C'est une demi-boule de verre d'indice N et de diamètre AB coupée en deux suivant le parallèle CD. On a approximativement :

$$MR=RM'.$$

Sur la face CD appartenant à l'une des deux moitiés, on déposé une couche d'oxyde de titane ou de tri-sulfure d'antimoine par vaporisation dans le vide et d'épaisseur optique $\lambda/4$. La lame de phase annulaire *EF* peut être placée sur *CD* dont le centre est occupé par un petit écrán opaque *R*. Les deux parties sont recollées puis on argente la face courbe sauf dans une petite région avoisinant le point *M'*. La préparation est en *M* au centre de la sphère *CM'D* et est éclairée par le condenseur non représenté sur la figure. Le condenseur porte dans son plan focal antérieur un anneau transparent sur lequel on forme l'image de la source. Après avoir traversée du condenseur, de la préparation et après réflexion sur le miroir sphérique *CM'D*, on a une image annulaire de la source sur l'anneau de phase *EF*. Un rayon diffracté par la préparation suit le trajet *MPQPM'* et on obtient en *M'* une image de la préparation, égale à la préparation et rigoureusement stigmatique. Grâce à la lumière cohérente, qui a traversé la lame de phase et qui aboutit en *M'* après avoir suivi le même chemin, l'image *M'* est une image en contraste de phase qu'il suffit d'observer avec un microscope ordinaire. L'écran opaque *R* sert à empêcher que les rayons lumineux pénètrent directement dans l'objectif sans avoir suivi le trajet indiqué. Un rayon tel que *MM'* effectuerait, en effet, un parcours 2 fois moins long que les rayons considérés précédemment. Il ne serait plus en cohérence de phase avec les rayons ayant subi la réflexion en *Q* et en *P* avant d'aboutir en *M'*. La lumière passant directement dans le système de *M* en *M'* joue le rôle d'un voile parasite qu'il est nécessaire d'éliminer par un petit écran opaque *R*. Les dimensions de cet écran sont toujours très petites et ne troublent en aucun cas la structure des phénomènes de diffraction.

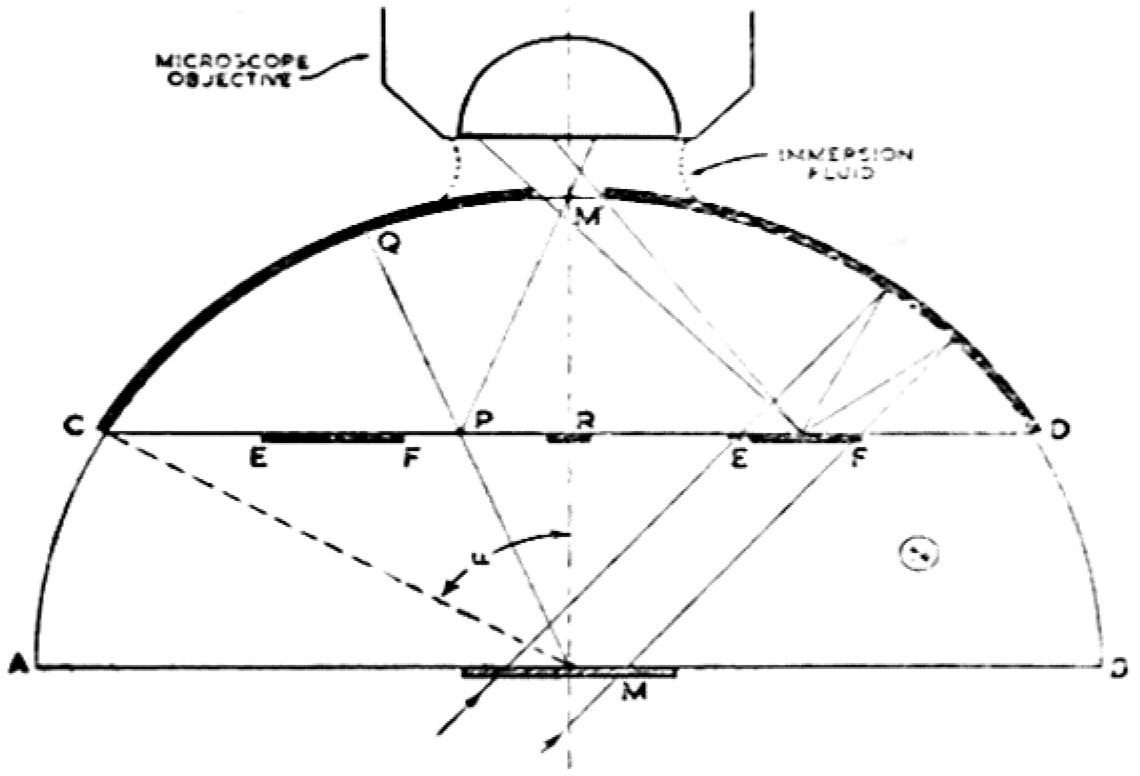

FIG. 12.1. Schema de l'appareil de contraste de phase.

L'ouverture maximum que peut donner l'appareil est obtenue lorsque le point *P* vient en *C* ou en *D*.

Pour $N=1{\cdot}52$ on a alors :

$$N \sin u=1{\cdot}32.$$

Pour le point M, centre de la sphère $CM'D$, le système est rigoureusement stigmatique. Mais si l'on s'écarte de l'axe, il apparaît de l'astigmatisme. Cette aberration ne sera pas gênante si la distance d'astigmatisme est inférieure à une certaine limite déduite, soit de la règle de Lord Rayleigh, soit de la règle de l'écart quadratique moyen. Dans ce dernier cas, si r est le rayon de la sphère $CM'D$, on obtient la condition :

$$r \geqslant \frac{2\sqrt{2}Nx^2 \sin^2 u}{\lambda}$$

où $2x$ est le champ linéaire et λ la longueur d'onde de la lumière. Pour un objectif de grandissement 100, d'ouverture $N \sin u = 1{\cdot}25$, on peut couvrir un champ de 10 mm. dans l'oculaire avec un rayon r de 20 mm.

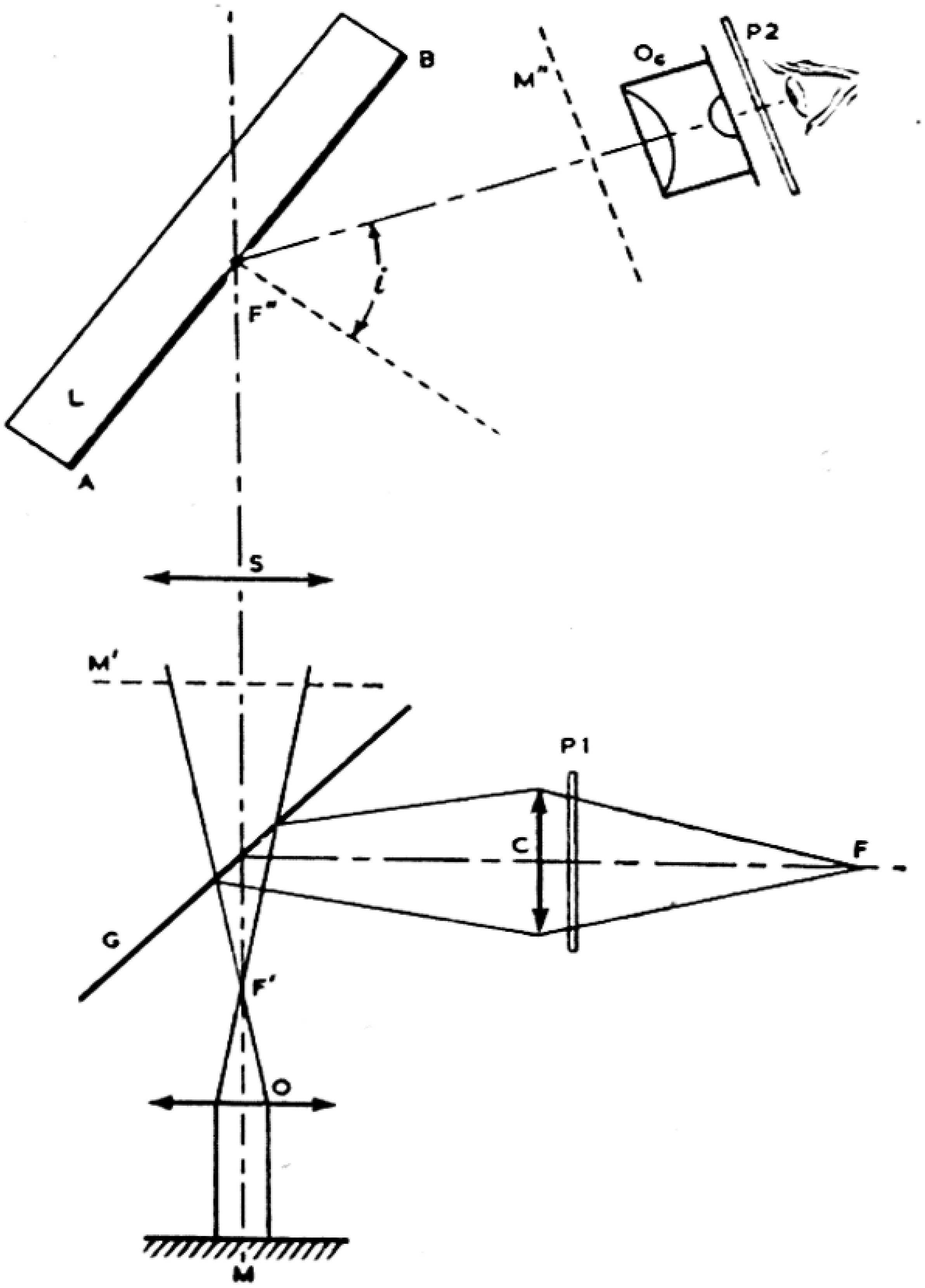

Fig. 12.3. Schema de l'appareil pour un objet reflechissant.

La figure 12.2 montre l'appareil monté sur le microscope. La liaison mécanique une fois réalisée entre le dispositif et l'objectif du microscope, la mise au point se fait comme d'habitude.

2. Dispositif à contraste de phase placé après l'oculaire

Nous décrivons le dispositif dans le cas d'un objet M réfléchissant (Fig. 12.3). L'illuminateur vertical du microscope est représenté schématiquement par la lentille C qui forme en F' une image de la fente source F. L'image F' se trouve au foyer de l'objectif O après réflexion sur la lame semi-transparente G inclinée à 45°. La préparation M reçoit un faisceau de rayons parallèles qui, après réflexion, reviennent sur eux-mêmes. Après traversée de G, les rayons rencontrent un système optique S (oculaire de projection) qui a pris la place de l'oculaire ordinaire.

On obtient ainsi en F'' une image de la fente F sur la lame de phase L. Cette dernière est constituée par une lame de verre dont une face AB, plane et bien polie, est recouverte d'un métal comme l'aluminium par exemple.

On a pris la précaution d'enlever l'aluminium dans une région ayant la forme d'une fente et sur laquelle viendra se former l'image F''. La lumière diffractée par les détails de l'objet M fournit en M' une première image, puis une deuxième image M'' après réflexion sur L. C'est cette dernière image que l'oeil observe au moyen de l'oculaire Oc. En F'' les rayons diffractés s'étalent autour de l'image de la fente et se réfléchissent sur l'aluminium. Si e est l'épaisseur de la couche d'aluminium et i l'angle d'incidence, on voit que les rayons directs réfléchis sur le verre en F' accomplissent un chemin optique plus long que les rayons diffractés réfléchis sur l'aluminium, la différence δ étant :

$$\delta = 2e \cos i.$$

En réglant convenablement e il est possible d'avoir le déphasage requis de $\pi/2$. Par suite de la réflexion sur le verre, la lumière directe est toujours plus ou moins polarisée ; en prenant $i=57°$ l'incidence Brewstérienne sur le verre, la polarisation est totale. Si on place alors un polariseur P^1 avant la lame de phase et un analyseur P^2 après la lame de phase, du côté de l'oculaire Oc, il est possible de faire varier l'intensité du faisceau diffracté par rapport au faisceau direct : on a une lame de phase à absorption variable. Si le polariseur P^1 est orienté à 45° du plan d'incidence de la lame L, il est possible en tournant P^2, de passer du contraste de phase positif au contraste de phase négatif et dans chaque cas, de faire varier l'absorption. La figure 12.4 montre le dispositif monté sur un microscope métallographique. La figure 12.5 représente l'aspect d'une lamelle couvre-objet de microscope. Les différentes rayures ne présentent pas d'intérêt, mais on peut apercevoir les défauts de poli sous forme de petites taches sensiblement circulaires et qui couvrent toute la photographie.

Lorsqu'on voudra utiliser le dispositif pour observer des préparations transparentes, il suffira de placer la fente source F dans le plan focal du condenseur comme d'habitude.

Lame de phase à absorption variable

Le plan CD est recouvert de tri-sulfure d'antimoine sauf dans la région annulaire EF qui est recouverte d'une couche de cryolithe d'épaisseur optique $\lambda/4$. Le rayon moyen de l'anneau de cryolithe est tel que les rayons issus de M le traverse sous l'incidence Brewstérienne. La lumière incidente est polarisée par un polaroïd placé en dehors du microscope et le diaphragme annulaire du condenseur est recouvert par une lame de cellophane 1/2 onde découpée d'une façon spéciale. En faisant tourner le polaroïd, il est possible de faire varier l'intensité de la lumière qui se réfléchit sur l'anneau de cryolithe avant d'arriver en M'. On a ainsi une lame de phase à absorption variable.

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SUMMARY

L'appareil que nous proposons est un vehicule de grandissement unitaire placé entre l'échantillon et l'objectif du microscope.

Il est rigoureusement stigmatique et aplanatique et permet l'utilisation des objectifs à immersion les plus puissants. Cet appareil produit un image en contraste de phase qui peut être observée à l'aide d'un microscope ordinaire comportant un objectif sans lame de phase. D'autre part, dans le cas des lames de phase très absorbantes on ne sera pas gêné par la lumière parasite, puisque l'absorption de la lumière a lieu avant d'entrer dans le microscope.

The apparatus which we propose is a vehicular system (magnification 1) that is placed between the sample and the objective of the microscope. It is absolutely stigmatic and aplanatic and makes possible the use of the most powerful immersion objectives.

This apparatus gives by itself an image in phase-contrast which can be observed with an ordinary microscope using objectives without phase plate. On the other hand, in the case of very absorbing phase plates, one does not have to worry about stray light, since the absorption of the light beam takes place before entering the microscope.

DISCUSSION ON PHASE CONTRAST MICROSCOPES

Mr. Smiles, at the request of the Chairman, gave an account of the application of phase contrast to the study of living cells by ultraviolet microscopy and showed photomicrographs illustrating this. The work is being carried out at the National Institute for Medical Research, London. Most ultraviolet studies have, in the past, been carried out in radiation of wavelength 2749A provided by the cadmium spark. Living mammalian cells, however, undergo physiological and morphological changes under prolonged exposure to this radiation. Fortunately there is a lag period before the appearance of structural changes. This allows several ultraviolet photomicrographs to be taken and these adequately represent the normal structure of the cells. The destructive effect of the ultraviolet radiation is progressive and is apparently initiated before morphological changes are evident; moreover, once the process has begun it may continue to operate even without further exposure to the radiations. For success in ultraviolet photomicrography it is, therefore, of the utmost importance to work quickly. The field must be chosen and exact focusing of the object carried out in visible light before exposures in ultraviolet are made, and there must be a minimum delay between successive exposures.

About 1926 Barnard developed a method for carrying out all preliminary adjustments in visible light. The field was chosen and focusing done by means of dark-ground illumination. The design of the microscope and method of mounting the visual and ultraviolet objectives allowed exact focusing of a selected field to be carried out before a single exposure in ultraviolet was made. This method has proved satisfactory for such objects as micro-organisms, but not for observing the presence and distribution of chromosomes in dividing mammalian cells. By phase contrast microscopy on the other hand, chromosomes and other cell organellae are revealed with the greatest clarity. It was, therefore, decided to use visual phase contrast in place of dark-ground illumination as the searching system for living cells. At the same time it was felt that the phase contrast unit could be designed so as to form an integral part of an ultraviolet phase contrast system.

Messrs. Cooke, Troughton and Simms of York have produced such a system in which the condenser is made of quartz. For searching, a glass lens is inserted in front of the annular aperture. The focal plane of the glass-quartz system lies in the plane of the exit pupil of the ultraviolet illuminating system when the glass lens is removed. Thus when the object is critically illuminated by visual light the quartz condenser is in adjustment for Köhler illumination in the ultraviolet. The visual phase contrast objective is corrected to work through a quartz coverslip. The annulus mounted on a slide can be removed to allow the use of the full aperture of the condenser in ultraviolet work. For ultraviolet phase contrast the same annulus is used and its centration is carried out with the aid of an auxiliary microscope in which the eye-piece is fitted with a fluorescent screen. It is thus possible to obtain comparative photomicrographs in visual and ultraviolet phase contrast, and in ordinary transmitted ultraviolet light. A fuller description of the system is being published shortly by Mr. W. E. Taylor.

Dr. R. Barer gave an account of work carried out at the Department of Human Anatomy, Oxford, by Dr. A. G. Oettlé using the Cooke variable phase contrast system. This system makes use of polarized light in order to obtain complete variability of both phase and amplitude. Both the direct and diffracted light can be absorbed at will. Slides were shown of various types of test objects which demonstrated that considerable departure from the use of a quarter-wave phase-plate often resulted in very little change in appearance of the object. Phase variation did not seem to be of very great practical value. On the other hand, variable absorption was sometimes useful, particularly in the study of very small objects. Under some conditions a spurious fringe or "optical membrane" appears around the image. Such effects are not confined to phase-contrast illumination. Absorption of diffracted light (the B type phase contrast of American workers) invariably resulto in image deterioration though it might in some cases reduce the harshness of the contrast. On theoretical grounds absorption of diffracted light is undesirable. A full account of this work will appear shortly in the *Journal of the Royal Microscopic Society*.

Some results of phase contrast in the infra-red using a photoelectric image converter tube were shown and described. Most stained biological sections are quite transparent in the infrared region when viewed by conventional methods of illumination. The detail in such specimens can, however, be revealed by phase contrast illumination. We thus have a method of optically unstaining a stained preparation and seeing what it would have looked like by phase contrast. Further details will appear shortly in the *Photographic Journal, Section B*.

Mr. J. Smiles stated that he did not use Kohler illumination in phase contrast work, but used critical illumination to obtain more light.

Mr. W. M. Lomer gave an account of some work carried out at the Cavendish Laboratory upon metal surfaces using an opaque annulus in place of the phase-retarding annulus. Images of irregularities, scratches, etc., thus appear bright on a dark ground. This technique is useful for the investigation of the surface topography of metal specimens after plastic deformation. He showed some similar observations obtained on rock-salt cleavage faces, and described how by using a decentred stop the effect of oblique illumination is obtained. (Cf. F. Zernike on *Phase Contrast*, in *Achievements in Optics* by Bouwers, Amsterdam, 1946.) This method enables high-power oil-immersion objectives to be used satisfactorily with oblique illumination. Where the precise interpretation of phase contrast images is of importance, a system which allows quick change-over between opaque, positive and negative phase contrast may thus be advantageous.

Dr. R. C. Faust said that central dark ground illumination obtained by using an opaque central stop in the objective did not give any guidance as to which parts of a phase object are elevated or depressed. If a phase step grating whose period consists of two unequally wide elements is so viewed under a microscope, the narrow element appears the brighter whether it be an elevation or a depression. If the element widths are equal the field should be uniformly illuminated, but due to departures from strict conditions the ruling edges actually appeared as narrow dark lines.

Phase contrast methods did, however, allow one to decide which regions are the more phase-retarding. An analogy can be drawn between variable amplitude phase contrast microscopy and interference microscopy of the two-beam Linnik type. Multiple beam interferometry can, on the other hand, be likened to phase contrast microscopy in which the phase strip is so wide as to alter to varying extends the amplitudes and phases of the higher order diffracted beams arising at the specimen.

Mr. J. Smiles pointed out the necessity of avoiding reflected light in view of its effect upon the halo and contrast of phase contrast images.

Mr. B. O. Payne gave an account of the system of Messrs. Cooke, Troughton and Simms which employs a specially constructed phase ring of quartz in two parts, together with a compensator, giving phase contrast with variable amplitude and phase. A full description of the system is shortly to appear (see: *J.R. Micro. Soc.* **70**, 225, 1950).

Professor L. C. Martin referring to the various methods of securing the requisite phase-change in the un-diffracted component of the light, considered that the method adopted by Messrs. Cooke, Troughton and Simms should lend itself to a fairly precise control, but in some cases one would like to know what guarantee there is that the supposed conditions have been attained. Even when the phase-plate functions perfectly, it should be remembered that the presence of any zonal spherical aberration, etc., in the objective may seriously upset the usually supposed phase relation between the direct light on the one hand, and all the various orders of diffracted components on the other. Moreover, the usual practice (almost inevitable) is to alter the focus until the image shows a contrast-pattern which the observer judges to be satisfactory. Adjustment of the focus is, of course, adjustment of the relative phases of the light entering the objective at various numerical apertures. It is to be feared that only too often the idealized picture of phase relations which is envisaged in the usual Zernike phase-vector diagram bears little relation to the truth, and the interpretation of the image is a difficult matter in which the microscopist will have to be guided, for the present, largely by experimental experience. The boundary wave conception explained in his recent paper in the *Proc. Phys. Soc.* would, he thought, be helpful in considering the phase contrast edge effects at the boundaries of large areas of uniform phase.

Dr. E. Linfoot pointed out that the statement made by Dr. Bouwers in describing his microscope system composed of refracting and reflecting surfaces, namely that when light passes at normal incidence through the refracting surfaces there would be no chromatic aberration, is not strictly true. He said that the halo effect in phase contrast microscopy could not be wholly due to surface reflection by fine detail in the specimen, as had been suggested. He agreed with Prof. Martin that the usual explanations of the phase contrast microscope were greatly oversimplified. The predictions of the simple theory would only apply to the finer detail and not to the field as a whole. A more complete theory would be excessively complex and an experimental approach seemed more hopeful.

Dr. R. Barer commented regarding Prof. Martin's criticism that conventional microscopy relied as a whole upon an incomplete theory. It was essential to adopt a critical attitude when observing as the evidence from such observations is only partial and needs supporting and corroborating by evidence obtained from the application of other techniques.

Mr. J. Dyson asked what would be the effect on phase contrast images of very large amplitude contrast which frequently exists in etched metal surfaces.

Mr. F. W. Cuckow replied that the simple theory of the phase contrast effect suggested that amplitude variations due to the specimen should be converted into phase variations in the image and so rendered invisible to the eye, but not enough had been done in the metallurgical field, as far as he was aware, to confirm such effects in practice. From the purely practical point of view, which was the theme of this meeting, it was probably better in difficult cases to attempt the suppression of all characteristics of the surfaces other than its geometrical form. A thin uniform layer of metal applied by evaporation in vacuo could be used for this purpose.

Professor F. Scandone, replying to Prof. Martin, considered things were "not so bad." He used a broad phase ring, in place of the narrow ring assumed theoretically, of dimensions resulting from practical test. He thought the result was to give a picture of the subject which was fairly accurate photometrically as regards fine detail but not necessarily so over larger areas: it resembled a good drawing rather than a half-tone picture. He had made observations on metallurgical specimens: the results were affected by phase differences on reflection.

Mr. F. W. Cuckow stated that the effect of phase changes on reflection had been considered in work of this sort. They appeared to be small but in cases where they might be important the techniques of coating the surface with a thin uniform metal film might be expected to suppress them. The possibility of such phase changes themselves yielding useful information should not however be overlooked.

SPECTROPHOTOMETERS

13. Spectrophotometry in the United States

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AS an introduction to a paper on spectrophotometry, one can hardly do better than to quote from the words of Dr. K. S. Gibson, Chief of the Photometry and Colorimetry Section of the National Bureau of Standards of the U.S.A. In a recent publication[1] he defines spectrophotometry as follows :

" Spectrophotometry is a term that by practically universal usage is taken to refer to the relative measurement of radiant energy or radiant flux as a function of wavelength. By strict derivation the term might be restricted to such measurements made visually, but in actual practice the word has long been applied also to photographic and photoelectric methods of measurement, in both the ultraviolet and the visible regions of the spectrum. More recently the term has been extended in application to cover also all such relative measurements in the infrared—throughout the region where the term ' spectroradiometric ' had heretofore been widely used, because the detectors necessarily used were of the type conveniently covered by the word ' radiometer.' The present extended usage is good, however, as it frees the word ' spectroradiometric ' for the absolute measurement of spectral distributions, as contrasted with the relative measurements for which the word ' spectrophotometry ' is so generally applied.

" The significance of the word *relative* in this connection is that in spectrophotometry the measurements are always made relative to some standard. What this standard may be in any case depends on the type of measurement. For example, in spectral reflection measurements it may be a standard magnesium oxide surface ; in transmission measurements it may be either the blank beam or a similar material or cell free of the absorbing constituent ; in measuring the spectral distributions of light sources it may be a source of known spectral distribution. But in all cases what is measured is merely the ratio of two quantities, wavelength by wavelength, throughout the spectral range of interest."

The present paper will not treat the older types of photographic and visual spectrophotometers, since these are being largely replaced by the more modern direct-reading or direct-recording instruments, and since the older instruments have been adequately described in many publications, two of the most recent of which are a book edited by Mellon[2] and a recent spectroscopy textbook[3] by Harrison, Lord, and Loofbourow.

The general trend in the *practice* of spectrophotometry is its emergence from the academic and industrial research laboratories and its acceptance in routine industrial testing and control. Another way to say this is that spectrophotometers are no longer to be recognized as highly specialised scientific instruments produced one at a time to individual specifications, but rather as fairly large-scale production items, as such things go. This change in production volume is reflected in the reduced cost of the instrument to the user and in the fact that he obtains a fairly standard item, the data obtained from which will be more-or-less readily comparable with data obtained in other laboratories or other plants.

The conventional way to discuss spectrophotometers is by the wavelength range which they cover, and that treatment will be followed here, using the headings *visible, ultraviolet,* and *infrared.* This is a classification based on practical grounds, since the visible instrument is chiefly employed in colorimetry, while the ultraviolet instrument is concerned with one general type of chemical analysis and the infrared instrument with another. There are other applications, however, where one wishes to make continuous measurements which include two or even three of these spectral regions, and here it might be felt that this classification is quite arbitrary. To be sure, many ultraviolet instruments can be used up through the visible region, but there is a natural division which occurs at about 1 or 1·2 microns : the division between the sensitivity region of the photoelectric cell and that of the thermocouple or bolometer. Another natural division of instrumental coverage is enforced by the nature of the light source. A tungsten filament lamp performs adequately over a large spectral region, say from 350 to 1500 millimicrons, but special sources are needed for the shorter ultraviolet and the infrared regions.

It will be noted that all the instruments described herein use the prism as the dispersing element. Despite the growing popularity of diffraction gratings in the field of spectrochemical analysis, the prism is still holding its own in commercial spectrophotometry.

Spectrophotometry in the Visible Region

The first spectrophotometric curve drawn completely by automatic means was obtained in the laboratory of Professor Arthur C. Hardy of the Massachusetts Institute of Technology on January 18, 1928. The instrument was described in a paper[4] written a few months later. A description of the commercial version which was built by the General Electric Company of Schenectady, New York, is given in a paper[5] published in 1935. The construction of the General Electric recording spectrophotometer was described[6] in 1938. Since in the fifteen years that this instrument has been in commercial service it has been referred to in so many articles and described in so many textbooks, it does not seem necessary to repeat its description here. Fig. 13.1 shows the familiar schematic diagram of the instrument.

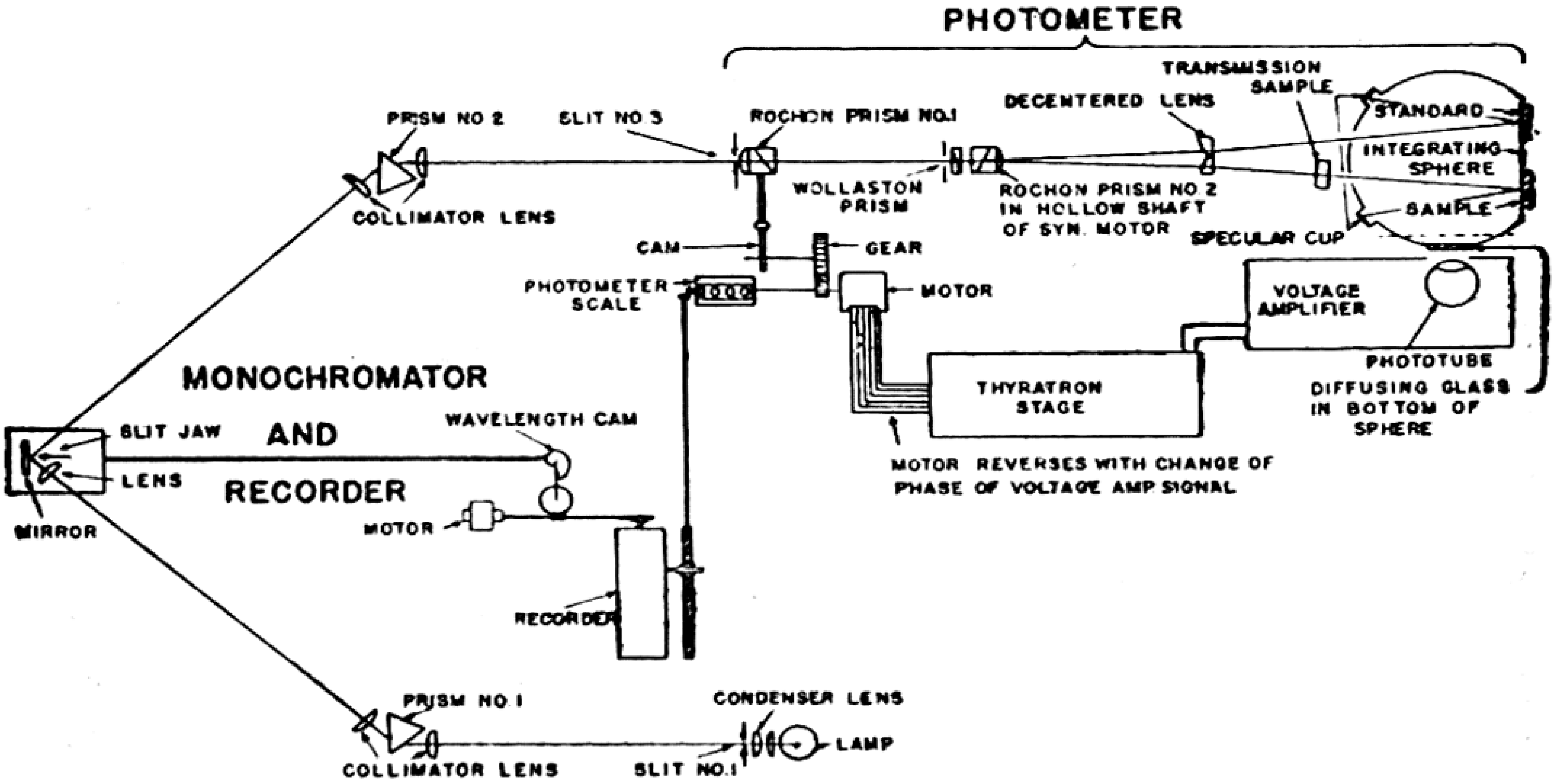

FIG. 13.1. Schematic diagram of the General Electric double beam, direct recording, photoelectric spectrophotometer. (*By courtesy of the General Electric Company, U.S.A.*)

This spectrophotometer is available in three models, to cover the nominal ranges 400 to 700 millimicrons, or 400 to 750 millimicrons, or the dual range of 400 to 700 or 750 and a subsequent range of 400 to 1000 millimicrons which has a non-linear wavelength scale.

With the presently available phototubes the range can be extended to 1100, and sometimes to 1200 millimicrons. The minimum wavelength that can be reached in the ultraviolet is 385 millimicrons.

An additional item of practical interest is the availability of an automatic tristimulus integrator which can be readily attached to the basic instrument.[7] It is stated that this gives tristimulus measurement and description of colour with a precision equal to that of the eye, and at no additional expenditure of time.

It should be emphasised that the Hardy-General Electric recording double-beam spectrophotometer is a very versatile instrument. Either transmittance or reflectance data can be readily obtained, and one can shift from running one kind of data to the other very quickly. The reflectance data can either include or exclude the directly (spectrally) reflected component, thus making it possible to measure gloss.

It is of practical interest to note that there are over 150 of these instruments now in use, of which a dozen are outside the continental United States. One way to estimate the actual nature of the employment of these instruments—for instance, as to research *versus* industrial control—is to examine the figures on the volume of recording paper which is specially printed up by the General Electric Company to cover the several ranges noted above, and to read in per cent. transmittance or reflectance, in optical density, or log density. Chart paper sales figures, when plotted against calendar years, give a rapidly rising curve which is evidence of the growing importance of these instruments in the colour and dye industries and in other situations where colour measurements must be made on an objective basis.

Ultraviolet Spectrophotometry

Satisfactory performance has been given by the Beckman Model DU Photoelectric Quartz Spectrophotometer in point-by-point ultraviolet spectrophotometry for almost ten years. This non-recording instrument, which is manufactured by Beckman Instruments, Inc. (formerly the National Technical Laboratories) of South Pasadena, California, was first described by Cary and Beckman in 1941.[8] It employs a quartz prism of the Littrow type in its single monochromator. For the short wavelength measurements from 200 millimicrons to the visible a small hydrogen discharge tube is used as the source, and this can be replaced by an automobile headlight bulb for measurements through the near ultraviolet and visible, and up to 1000 millimicrons. Two different phototubes are supplied, one for the range 200 to 625 millimicrons and the other for the range 600 to 1000 millimicrons, or perhaps 50 millimicrons further into the infrared. The circuits must be balanced at each wavelength selected before a reading of the sample is made, and the transmission data which are obtained can be plotted subsequently to give the usual transmittance *versus* wavelength curve. This is hence far from being an automatic instrument, but good accuracy can be achieved, at the expense of operator time. The scale also reads directly in optical density. An attachment is supplied by which directional reflectance measurements can be made through the visible and into the ultraviolet to about 350 millimicrons. An evaluation of the utility and accuracy of the Beckman DU spectrophotometer in spectral transmission and absorption measurements has been made by Gibson and Balcom.[9]

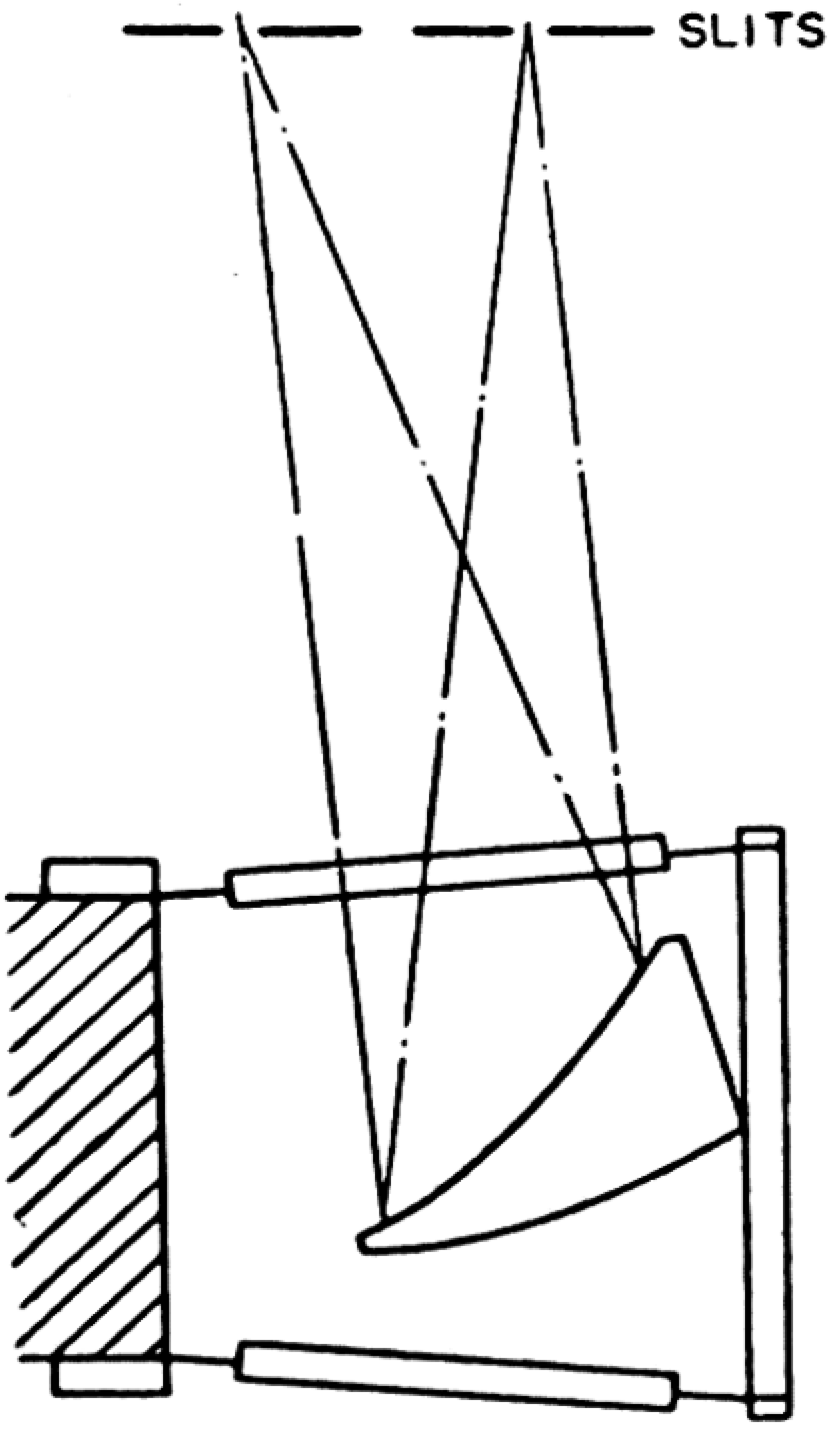

FIG. 13.2. Féry prism arrangement in the Beckman Model B glass spectrophotometer. (*By courtesy of Beckman Instruments, Inc.*)

A simpler instrument for the range 320 to 1000 millimicrons has recently been announced.[10] This has a very simple optical system, which comprises two slits, one plane mirror, and a Féry borosilicate crown glass prism, the mounting and focusing scheme for which is shown in Figure 13.2. This quadrilateral hinged mounting effects the desired simultaneous rotational and translational motions of the prism in changing the spectral region. The slits can hence be fixed in location. The general operation of this instrument is similar to that of the Model DU. The transmission scale reads from 0 to 100 per cent., and the density scale from 0 to slightly above 1·0. The instrument operates entirely from 110 volt alternating current, so no storage batteries are required.

An automatic-recording, double-beam spectrophotometer for the ultraviolet and visible regions has recently been designed by Howard Cary and is manufactured by the Applied Physics Corporation of

Pasadena, California. Its double monochromator, shown in Fig. 13.3, gives high dispersion and freedom from scattered light. This instrument is currently available in three different models. In one model the 11-inch wide chart reads directly in per cent. transmittance, and in another it reads directly in optical density, both *versus* linear wavelength. The nominal wavelength range of these two instruments is 220 to 600 millimicrons, and is limited by the sensitivity of the IP28 photomultiplier tube. It is sometimes possible to increase this range to from 200 to 800 millimicrons. The third model of the instrument employs an experimental cesium oxide photomultiplier tube and a special monochromator to extend the range to 1200 millimicrons. The scanning rate can be varied from 0·1 millimicrons per second to 10 millimicrons per second, but of course with a consequent sacrifice of resolving power. A diffuse reflectance attachment comprising two integrating spheres is available, with which reflectance curves can be obtained in the range 240 to 800 millimicrons. This appears to be an excellent, rapid survey instrument for the ultraviolet and visible regions, but the necessarily limited width of the recording chart paper imposes some restrictions on the quantitative accuracy obtainable.

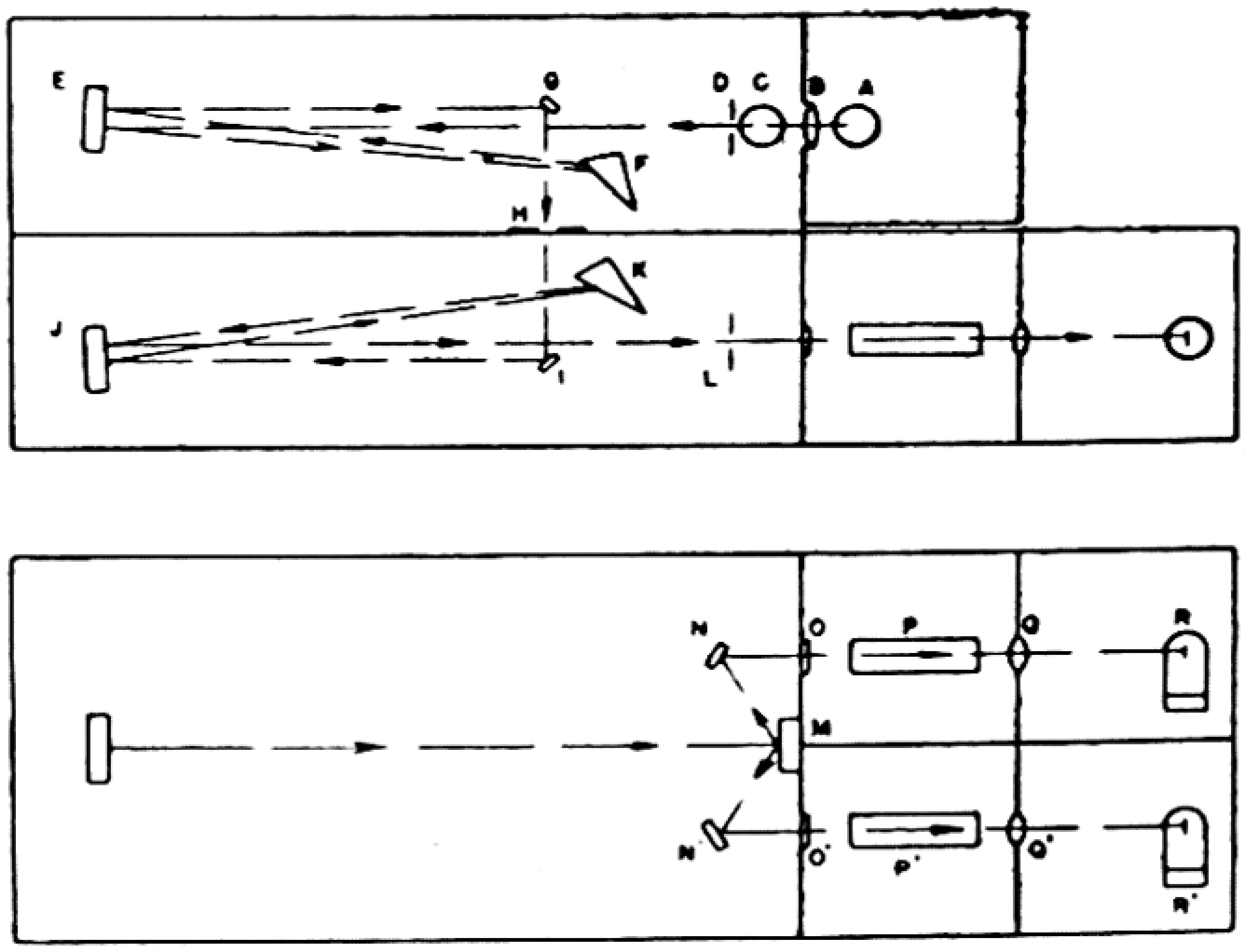

FIG. 13.3. Schematic optical system of the Cary double beam, direct recording, ultraviolet spectrophotometer. (*By courtesy of the Applied Physics Corporation*.)

Infrared Spectrophotometry

This is the largest of the treatments of spectrophotometers, since there are at least a half-dozen instruments which can be classified as commercial infrared spectrophotometers. This is all the more unusual since up to 1940 or thereabouts infrared instruments were built according to individual needs and designs, and were seldom to be found outside academic or perhaps industrial research laboratories. During World War II, however, the infrared spectrophotometer proved that it was a satisfactory and rapid tool for quantitative organic analysis and for plant control in the manufacture of such vital materials as aviation gasoline and synthetic rubber. In the following years it was discovered that many other types of organic analysis and industrial control in chemical plants could be handled effectively and inexpensively by infrared methods. The impetus given the field by this strong commercial interest is hence reflected in the good instruments which are now readily available and in improved features of design which have been developed. A brief review of this rapid development has been given recently by Barnes and Gore,[11] who list over 300 literature references.

The outstanding advance, from a practical point of view, is probably the substitution of stable electronic amplifiers and rugged recorders for the older and much less satisfactory galvanometers. Great strides have also been made in the very difficult technical problems associated with overall stability of the instruments, including such items as minimizing fluctuation of the energy source, decreasing the effects of varying ambient temperature on the wavelength and photometric systems, and eliminating zero drift of the detector and the effects of scattered light and other forms of false energy.

Before discussing specific instruments, a few remarks of a general background nature should be made. Infrared instruments can be classified under several different types or headings. There are single beam and double beam instruments; there are instruments whose data must be replotted after correcting for the energy curve of the thermal source and the absorption of the atmosphere in order to give a per cent. transmittance curve, while others give a direct record of per cent. transmittance (or perhaps optical density) *versus* wavelength or wave number; and finally, there are the versatile research-type instruments, or there are those which are designed particularly with a view to maximum stability and reproducibility, for routine quantitative analysis. It can be stated that the trend has been definitely in the direction of the instruments which record sample transmittance *versus* wavelength directly on a moving chart, although in some cases this is done at the expense of ultimate analytical accuracy. No clear decision has yet been reached between the single beam—memory type and the double beam instruments, as is indicated below. In general, a purchaser of an infrared spectrophotometer should have clearly in mind a hierarchy of proposed uses for the equipment before he makes a final choice.

With regard to wavelength region covered, the rather standard ranges are two : the rock salt range which extends into the infrared to about 15 microns, and the potassium bromide range which extends to about 25 microns. Some instruments can be equipped with a prism of thallium bromide-iodide (KRS-5) which permits extension of the useful range to perhaps 40 microns. Some instruments can employ prisms of lithium fluoride or calcium fluoride in order to obtain maximum dispersion and resolving power out to 6 microns and 9 microns respectively.

All current instruments employ either the Littrow or the Littrow-Wadsworth prism arrangements, usually with off-axis parabolic mirrors. Either the entrance or the exit slit of the monochromator should be curved to correspond with the curvature caused by the prism. As a radiation source in the infrared either the Globar or the Nernst glower is used. As a thermal receiver, a thermocouple or thermopile, or either a metal or a semi-conducting bolometer is ordinarily employed, although the Golay pneumatic detector is sometimes used. These various matters will not be treated here in more detail since they are reviewed in the admirable paper[12] on infrared instrumentation and techniques by Van Zandt Williams, where references to the original publications are to be found.

One difficulty which is encountered very seriously in the infrared is that the above-noted thermal sources have their maximum emission at around 2 microns wavelength, so that as measurements are made further and further into the infrared the available energy decreases rather rapidly. In working with a simple, single beam spectrophotometer, it is hence necessary to increase the slit width from time to time. From the practical point of view this means that in running a complete spectrum with a single beam instrument like the Perkin-Elmer Model 12, it is necessary to go through the spectrum running an energy curve which has a number of discontinuities where the slit width is changed, and then go back and repeat the operation with the sample in place. The desired transmittance *versus* wavelength curve is then drawn separately, by referring to the curves obtained in the two runs. This is a rather time-consuming procedure when large spectral ranges are involved, and hence various means have been proposed for obtaining the per cent. transmittance curve directly. One method employed here is to vary the signal amplification or the slit width continuously while scanning the energy spectrum of the thermal source, so as to give, on the recording chart, a straight line which is the 100% transmittance curve. The slit width needed to do this is recorded by a memory device such as a magnetic tape. The sample is then introduced into the light path, and the spectrum is again scanned, but this time with the " playback " of the memory device adjusting the slit width to the previous values, wavelength by wavelength. The desired transmittance *versus* wavelength curve is hence obtained automatically. Advantages claimed for this method are the simpler single beam optical system and the avoidance of duplicate sample cells and the necessity of obtaining close matching of cell characteristics, since during the standardisation run the regular absorption cell can be used either empty or solvent filled. The other method is the so-called " double beam " method in which the light from the thermal source is split, usually by a rotating shutter, and goes alternately through the sample beam and a beam containing an empty, or solvent filled, matched cell. These two beams are then brought together at the entrance slit of the monochromator. The two beams are put into intensity balance by a neutral wedge or a comb which is forced into the reference cell beam by a servomechanism actuated whenever a fluctuating signal is given by the bolometer or thermocouple. The position of the wedge or comb is recorded as per cent. transmittance. The signal amplifier, being a null detector, need not be linear, and need have only sufficient constancy of gain to insure servomechanism stability. At the present time some commercial instruments use one of these two methods of giving per cent. transmittance automatically, while other instruments use the second method. It appears that the double beam method is somewhat faster and more adaptable, while it is claimed that the memory device method is capable of more accurate quantitative work. But these points of view are subject to change as the development of this rather complicated type of instrumentation proceeds, year after year.

Several of the currently available types of infrared spectrophotometers will now be described very briefly, and in roughly historical sequence.

The Beckman Infrared Spectrophotometer Model IR2 is manufactured by Beckman Instruments, Incorporated (formerly the National Technical Laboratories) of South Pasadena, California.

The fundamental design is similar to that of the Beckman quartz spectrophotometer Model DU, which is referred to above. It consists of a rugged, closed monochromator to which may be added other units such as radiation sources and receivers, and absorption cell compartments for solid, liquid, or gaseous samples. The schematic optical path of the IR2 is shown in Fig. 13.4. The infrared radiation from the Nernst glower is interrupted at a frequency of 10 cycles per second, and the amplifier used in connection with the radiation detector is tuned to a frequency of 10 cycles per second, so that although the photoreceiver detects all infrared radiation falling upon it, only the pulsating radiation is amplified and measured. One shutter is metal for use in the shorter wavelengths to 9 microns, and the other is thin glass for use beyond 9 microns. The glass shutter serves to correct for the false energy because it does not interrupt the scattered light which is concentrated in the region around the energy peak of the glower near 2 microns. Since this radiation is not interrupted, its effect is ignored by the frequency selective amplifier. This basic advantage over the double beam type of instrument should be noted. The radiation output of the Nernst glower is held constant automatically within 0·1% by a special photoelectronic regulator, *R* of Fig. 13.4. In addition to the usual wavelength dial and motor-drive coupling shaft, there is a turret stop mechanism which permits setting immediately to any one of 17 previously selected wavelengths. The entire monochromator is of course desiccated, and is held at constant temperature by the circulation of a temperature-controlled fluid, ensuring constant wavelength calibration. Apparently this instrument was designed for maximum stability, reproducibility, and ruggedness, which suggests its special use in the routine quantitative analysis of multi-component mixtures. Although it can be motor-scanned in wavelength and fitted with a recorder, for survey work, the point by point method is probably preferable for

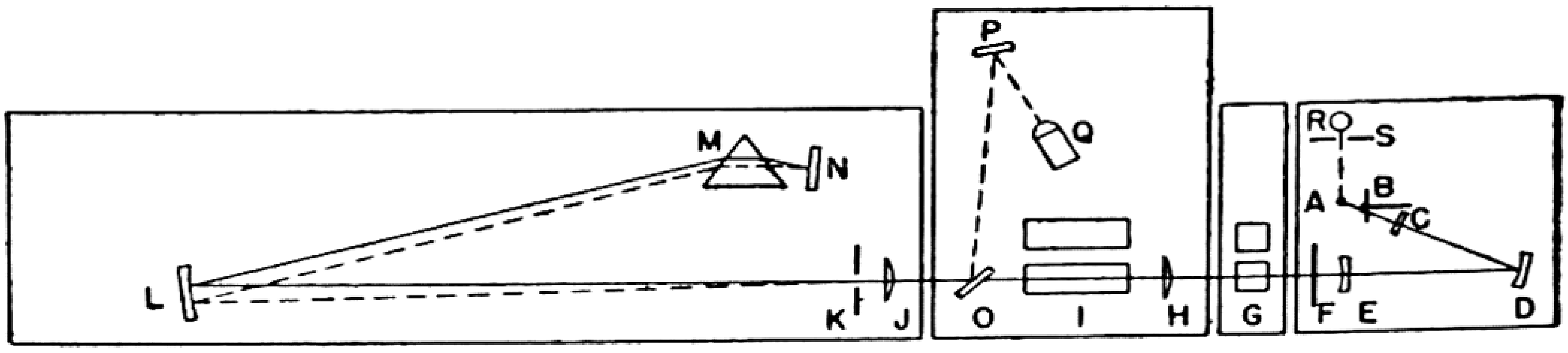

FIG. 13.4. Schematic optical system of the Beckman Model IR2 infrared spectrophotometer. (*By courtesy of Beckman Instruments, Inc.*)

the most careful quantitative work. The scale reads both in per cent. transmittance and optical density, for maximum convenience.

The Model 12 recording infrared spectrometer manufactured by the Perkin-Elmer Corporation of Glenbrook, Connecticut, is another single beam instrument which is in wide use. Again, the instrument consists of a single monochromator with additional units for sources, receivers, absorption cells, etc. A motor drive can be added to the wavelength control and a recorder employed, or the instrument can be used in a point by point fashion. Thermocouple drift, the bane of infrared spectroscopy, is effectively eliminated by checking the zero drift five times a second with the rotating shutter. Voltages due to drift are removed from the resulting five-cycle signal by filtering them out and feeding them back into the thermocouple circuit with the proper polarity to cancel out almost all of the thermocouple's direct current output. The five-cycle current is finally rectified mechanically and filtered to give a steady direct current output suitable for recording. A special vacuum thermocouple is manufactured by the Perkin-Elmer Corporation for use with this instrument. The Model 12C instrument operates entirely on alternating current, thereby doing away with the need for storage batteries. A gas absorption cell with an optical path of one meter can be furnished for this unit, as well as the usual liquid cells. The outstanding feature of this spectrophotometer appears to be its versatility and adaptability to many uses. Thus it is useful for the problems arising in research laboratories, as well as in analytical laboratories. The monochromator section of the instrument can now be furnished separately from the other sections, for those persons who have special purposes in mind and can benefit by the use of such a compact, well-engineered unit. Prisms of the several materials referred to above can readily be interchanged in this flexible instrument.

The first commercial infrared instrument to give a direct per cent. transmittance recording automatically is the infrared recording spectrophotometer manufactured by Baird Associates, Inc., Cambridge 38, Massachusetts. This design[13] followed earlier suggestions made by J. D. Hardy, N. Wright, and others. The double beam principle referred to above is employed in this instrument, whose optical system is shown in Fig. 13.5. The source is a Globar and the radiation receiver is a platinum strip bolometer. The electronic amplifier is tuned to the interrupter frequency of 10 cycles per second. The scanning speed control comprises a selector switch, two synchronous motors, and a differential gear mechanism. It permits scanning the spectrum at three speeds. Normal speed requires 12 minutes to cover the rock salt range from 2 to 16 microns; slow speed requires 24 minutes to cover the same range. Fast speed is used to move more quickly from one portion of the spectrum to another. The chart length is 17½ inches, and covers the range 12 to 26 microns for the potassium bromide prism. Capillary absorption cells for highly absorbing liquids, or gas cells up to 10 centimetres in length can be employed. A special device can also be used which permits the reflectance of solid samples to be measured throughout the infrared region. This instrument has proved very popular as a survey and identification device for use over the rock salt and potassium bromide regions. Its stability and very simple operation,

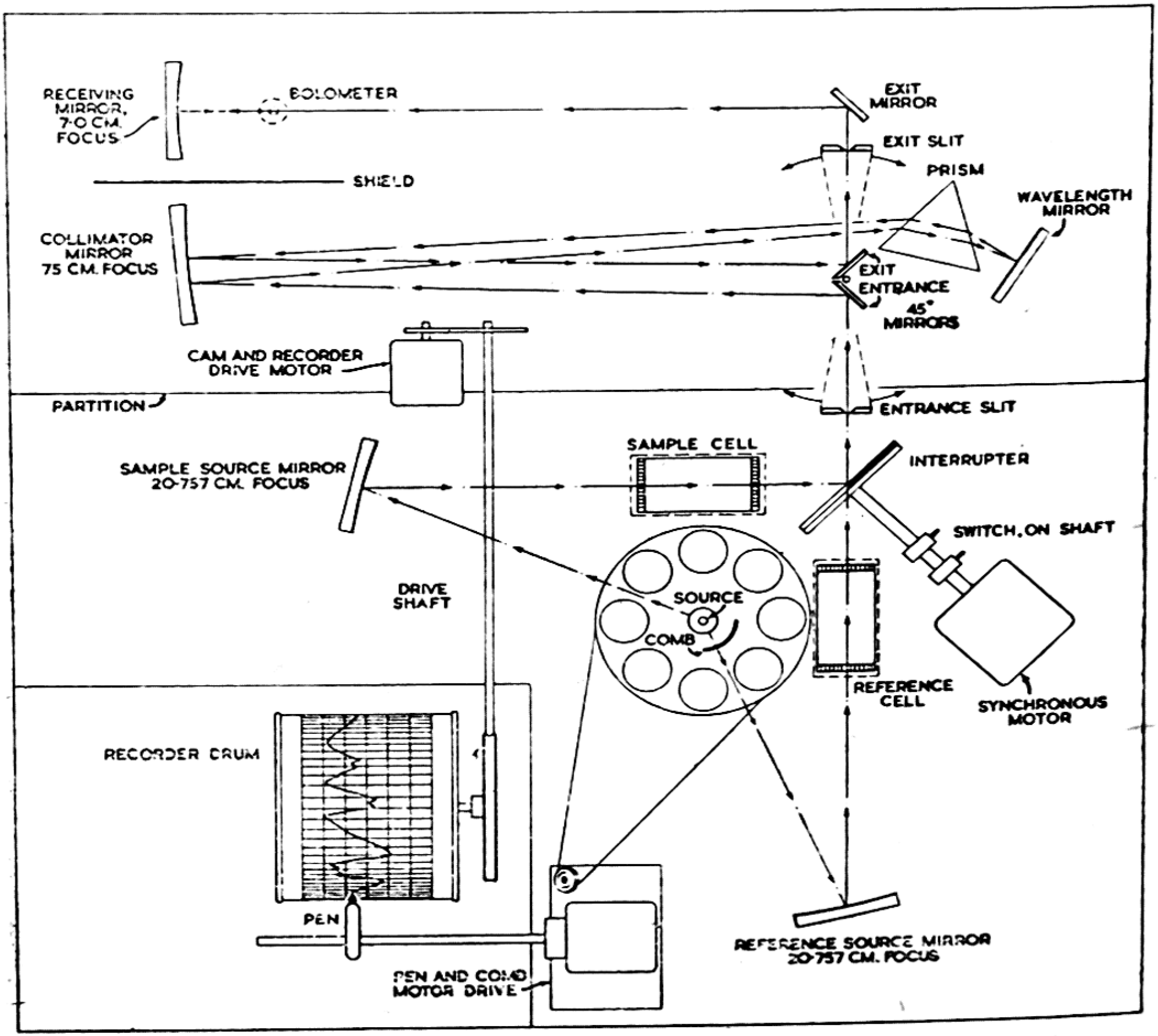

FIG. 13.5. Schematic optical system of the Baird Associates double beam, direct recording, infrared spectrophotometer. (*By courtesy of Baird Associates, Inc.*)

and its high speed of delivering per cent. transmittance records, are among its outstanding features.

The Perkin-Elmer Corporation has recently announced a double beam recording infrared spectrophotometer, the Model 21, whose characteristics are described in a series of three papers[14]. This instrument retains a great deal of the versatility of the Model 12, while employing the double beam and direct-recording-of-per-cent. transmittance principles. Fig. 13.6 shows the optical system schematically, and also includes block diagrams of the various electronic circuits. An explanation of the details of these various features can best be obtained from the papers of reference 14. The wavelength scanning speed can be varied so as to take from about 5 minutes to 200 hours to cover the rock salt region, with a concomitant variation in the resolving power. Paper drive speeds can give uniform scales between the extremes of 1 and 50 inches per micron. Prisms of lithium fluoride, potassium bromide, and perhaps other materials can also be employed. The chart size is 34 inches by 11 inches. Five inches of length is available for sample cells in each beam. The same

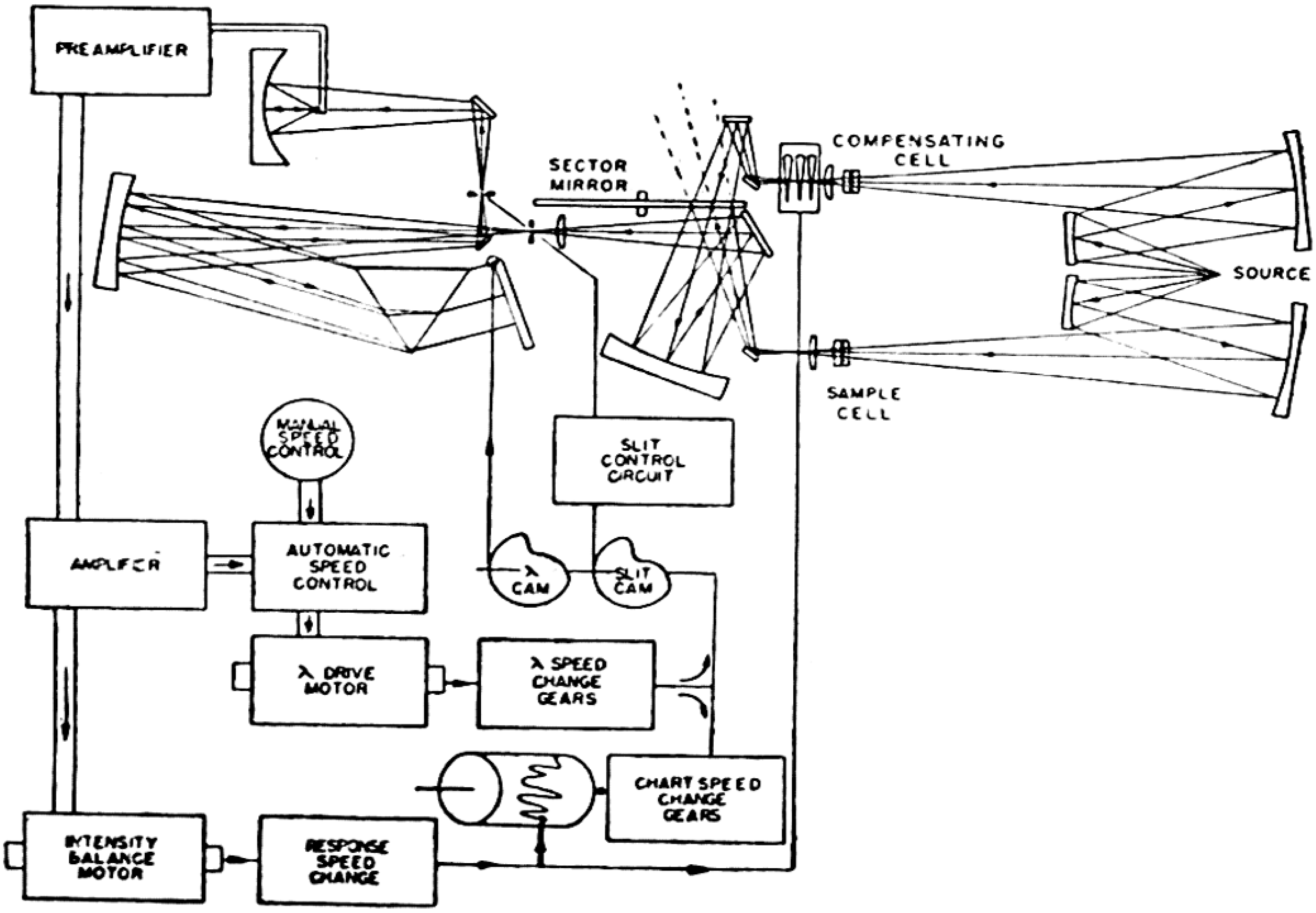

FIG. 13.6. Optical system and block diagram of the Perkin-Elmer Model 21 double beam, direct recording infrared spectrophotometer. (*By courtesy of the Perkin-Elmer Corporation.*)

thermocouple detector is used as in the Model 12 instrument, but the light beam is chopped at 13 cycles per second. Since this instrument has made its appearance only very recently, it is not yet possible adequately to evaluate all its features. Its extreme versatility, coupled with the direct-recording feature, seem to characterize it as a powerful instrument for research projects in the infrared region.

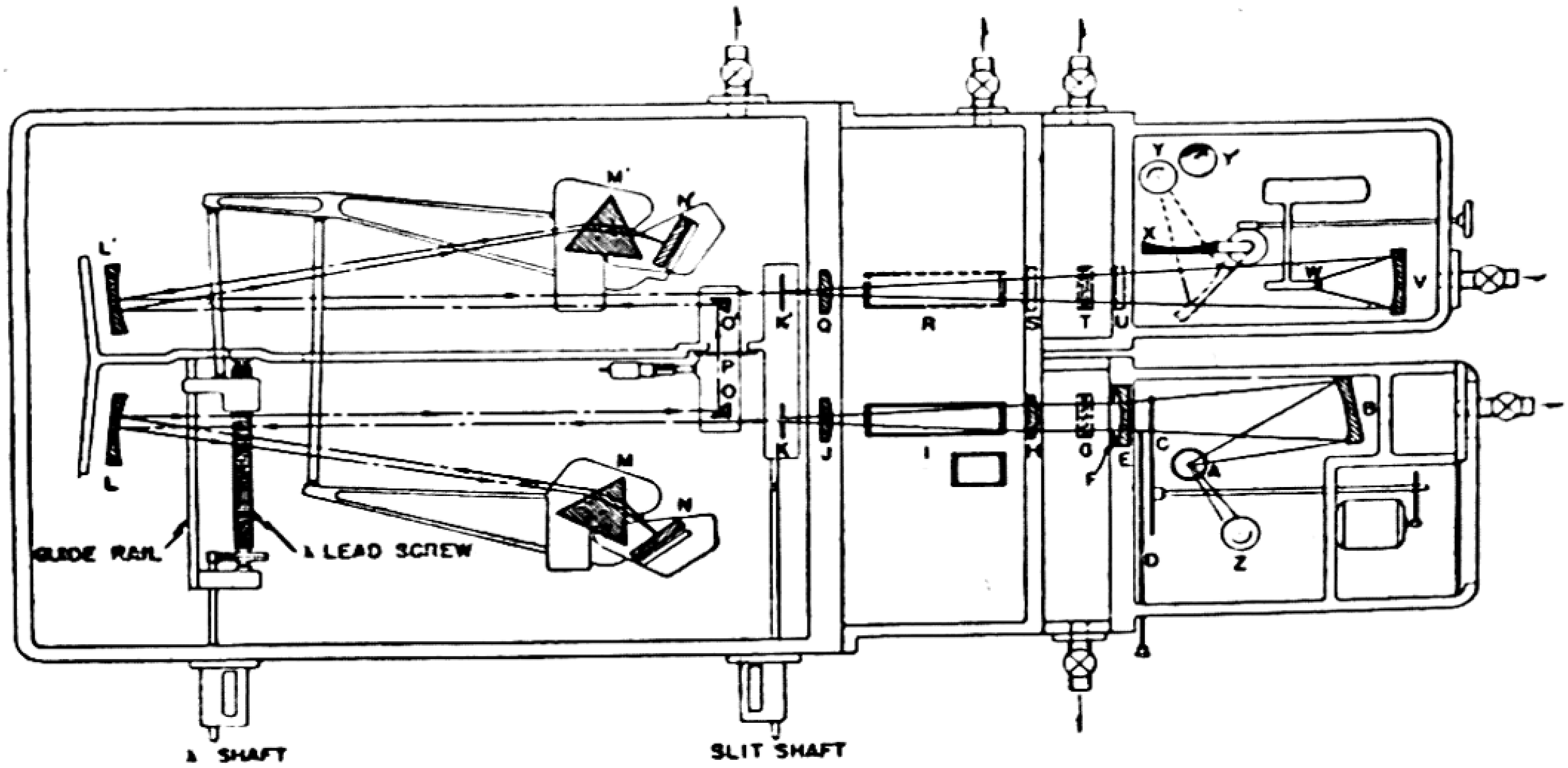

FIG. 13.7. Optical system of the Beckman Model IR3 double monochromator, single beam, memory device, direct recording spectrophotometer. (*By courtesy of Beckman Instruments, Inc.*)

Another new instrument is the Beckman Model IR3 direct transmittance recording research spectrophotometer. This is a single beam, double monochromator instrument that employs memory standardisation to obtain direct transmittance recordings *versus* either wavelength or wave number. The 100% reference level for direct transmittance recording is automatically determined by making a standardising run against an empty or solvent filled sample cell. The automatic slit control system maintains the amplified photoreceiver signal constant and is so arranged that the slit width *versus* wavelength function is recorded on a wire recorder. On subsequent "play-back" the wire recorder controls the slit and wavelength servo motors, precisely reproducing the standardising conditions so that absorption spectra from a sample are recorded directly in transmittance. Slit-width control has the advantage that the instrument is always working at maximum resolution for any chosen signal-to-noise ratio and recording speed. Furthermore, recording accuracy and reliability are not lost through regions of solvent and background absorption.

Fig. 13.7 shows schematically the optical path of the complete instrument. Advantages claimed for the double monochromator arrangement are the cancellation of aberrations from one half of the monochromator to the other, the substantial elimination of stray light, and the utilization of the full resolving power computed for four passages of the light beam through the prisms. This instrument utilizes a scanning system which achieves maximum operating efficiency by traversing each spectral slit width in a time proportional to the response period of the recording system. The entire optical path can be evacuated to eliminate water vapour and carbon dioxide absorption. The spectrophotometer is entirely thermostatted. Recording speed is automatically maintained at the maximum consistent with the resolving power of the spectrometer and the chosen recording conditions. The chart size of 65 inches by 10 inches gives a wavelength scale of 0·2 microns per inch for the rock salt range. Other scales can be obtained by changing gears in the chart recorder. Again, this instrument is so new that too much comment cannot be made as yet on its performance in a number of different laboratories and under a variation of operating conditions, and in the solution of widely diverging types of problems. It would seem, however, that in view of the features listed, it surely represents the ultimate obtained to date in many practical aspects.

The general memory type of instrumentation described for the Beckman IR3 is also available, in appropriate form, as an attachment for the Model IR2 described above. This converts the IR2 into an instrument that records per cent. transmittance *versus* linear wavelength directly. This combination is often referred to as the "IR2½." It must be remarked that while this appears to be a useful conversion to make, for laboratories that already possess an IR2, the resulting combination falls far short of the instrumental excellence of the IR3 with its double monochromator and several other very attractive features.

Finally, two current developments are worthy of mention. The first of these is the use of a multi-slit arrangement in an effort to increase intensity in a monochromator by a significant factor such as 20 or 30. This was reported by Golay[15] in 1949, and it is understood that considerable experimental work has been carried out since that time. However, no additional information is now available to the writer. The other is a development by Savitzky and Halford[16] for converting a single beam spectrophotometer such as the Perkin-Elmer Model 12 into a double beam instrument for direct recording of transmittance *versus* wavelength. A phase discrimination system is used which requires no changes in the optics and no sacrifice of versatility or ease of prism interchange. The method consists of chopping the upper and lower halves of the beam, 90 degrees out of phase with each other. The sample cell is also divided into two parts: one part for the solvent or blank, the other for the solvent-plus-sample or the sample alone. This system is readily adaptable to other spectrophotometers, including those in the visual and ultraviolet ranges, the only limitation being sufficiently rapid response by the detector. A Golay pneumatic detector has been employed in the experiments carried out thus far, to take advantage of its high speed of response and sensitivity.

Summary and Conclusions

In conclusion, it is seen that there is available a fairly wide choice of instruments for spectrophotometry in the ultraviolet, visible, and infrared regions of the spectrum. It appears that the situation for making transmittance measurements is adequate between the wavelengths of 200 millimicrons and 40 microns. The situation for reflectance measurement is not so satisfactory, however, due chiefly to the lack of sufficiently intense sources in the deep ultraviolet and the infrared. It is hoped that this situation can be remedied in the not too distant future.

Since some of the instruments described have become available only relatively recently, it is not possible at this time to give a very thorough evaluation of them—they will have to stand the test of time, as some of the older instruments have done so successfully. Also, new methods are still being investigated, and complete new instruments may make their appearance at any time. An item of current developmental interest which has not been discussed herein is the cathode-ray presentation method for rapid scanning of the spectrum.

No claims whatever are made for the exhaustiveness of the present treatment, as should of course be well understood by the reader. The selection of instruments described, it must be admitted, can be traced back to such arbitrary factors as the writer's personal familiarity with these particular instruments, although it is hoped that the errors of omission are not too serious or too numerous. No attempt has been made, in this brief treatment, to give *all* the details and features of any or all of the instruments. Many of the items mentioned, particularly the accessories, may be as applicable to one instrument as to another. The catalogues of the various manufacturers should be consulted for more details than were deemed appropriate for discussion herein.

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SOMMAIRE SUMMARY

Le developpement de la spectrophotometrie aux Etats-Unis a été vers des instruments à rayon double enrégistrent automatiquement et rapidement.

Le premier instrument de cette sort qui a eu du succés a été développé par A. C. Hardy de l'Institut de Technologie de Massachusetts. Il a été d'abord déssiné à comprendre le spectre visible (400–700 mμ) mais sa portée a été éntendue plus tard une petite distance dans l'U.V. et aussi loin dans l'I.R. que la sensibilité des cellules photoélectriques actuellements procurables permit.

La région spectrale suivante dans laquelle la photométrie automatiquement enrégistrée a été achevée étrait l'infa-rouge, un fait qui se doit probablement à la presse des chimistes organiques pour une méthode analytique plus rapide. Un instrument automatique qui comprend les regions du sel gemme et du potassium bromide a été développée en 1947 et dans beaucoup de laboratoires industrielles les spectromètres précédents de l'infra-rouge sont supplémentés par un des instruments enrégistrants à rayon double. Dans la régime de l'U.V. le Beckman instrument de quartz à rayon

unique a été largement employé. Un instrument moderne, automatique à rayon-double pour les règions U.V. et visibles à été récemment dessiné par Howard Cary.

La situation actuelle du mésurage de la transmission des exemples entre les limites de longeur d'onde 200 mμ et 25 μ est maintenant relativement satisfaisante hors de difficultes d'intensité dans l'I.R. distant. Tout de même il est nécessaire de développer des sources plus claires avant qu'une sensibilité suffisante est profitable aux mesurages de la réflexion dans les régions de l'U.V. et de l'I.R.

On s'intéresse à la méthode de présentation par le rayon-cathodique pour l'examen rapide du spectre et aux nouveaux projets comme ceux de Golay et de Savitzky pour obtenir des intensités plus grandes et la construction plus simple et moins chère d'un instrument à rayon-double.

The trend in the development of spectrophotometry in the U.S.A. has been toward rapid-acting, automatically-operating instruments which record per cent. transmittance or reflectance, or optical density, directly *versus* wavelength. The first successful instrument to meet these requirements was developed some twenty years ago by Arthur C. Hardy of the Massachusetts Institute of Technology, and is available commercially from the General Electric Company. It was originally designed to cover the visible spectrum (400 to 700 millimicrons), but its range has subsequently been extended a short distance into the ultraviolet, and as far into infrared as the sensitivity of currently available phototubes permits. The next spectral region in which automatic, percent recording spectrophotometry was achieved was the infrared, a fact which was probably due to the pressure from organic chemists for a faster analytical tool. Baird Associates, Incorporated, of Cambridge, Massachusetts, announced in 1947 an automatic instrument which covers the rock salt and potassium bromide regions, and they have been followed by instruments from the Perkin-Elmer Corporation of Glenbrook, Connecticut, and Beckman Instruments, Incorporated (formerly the National Technical Laboratories) of South Pasadena, California. While the familiar Perkin-Elmer Model 12 and Beckman IR2 single beam, point-by-point instruments are still performing their functions faithfully and adequately in many laboratories and industrial plants, it can be expected that the newer direct-recording instruments will become more and more numerous. In the ultraviolet and visible regions the Beckman quartz single beam, point-by point instrument has enjoyed very wide use. A modern, automatic percent recording, double beam instrument for the ultraviolet and visible regions has recently been designed by Howard Cary and is manufactured by the Applied Physics Corporation of Pasadena, California.

The present situation for measuring the transmittance of samples between the wavelength limits of 200 millimicrons and 25 or perhaps 40 microns is now relatively satisfactory except for intensity troubles in the far infrared. Brighter sources must be developed, however, before adequate sensitivity is available for reflectance measurements in the infrared and the deep ultraviolet regions.

14. Equipement et méthodes spectrophotométriques pour le domaine 0·36—1·2 micron, utilisés à l'Institut d'Optique de Paris

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En dehors de certains dispositifs de contrôle, l'équipment pour travaux spectrophotométriques courants mis au point par l'Institut d'Optique comprend actuellement :

(a) Pour l'infra-rouge

(1) Un spectrophotomètre de Bayle[1], comportant un monochromateur simple à prisme de chlorure de sodium et miroirs et une thermopile compensée[2], appareil utilisable jusqu'à 5 microns avec une lampe à filament de tungstène et jusqu'à 15 microns avec une lampe Nernst.

(2) Un monochromateur double à prismes de flint et miroirs[3] associé à une lampe à incandescence et à un récepteur thermoélectrique à optique de quartz pouvant recevoir, soit un thermocouple dans le vide de Kipp, soit une thermopile compensée de Bayle ; cet ensemble permet d'explorer le domaine 0·6–1·9 micron avec une bonne précision sur les mesures photométriques et sur la longueur d'onde.

(b) Pour le visible

(1) Le même monochromateur que ci-dessus associé à un photomètre photoélectrique dit " Amplificateur photoélectrique "[4] permettant de travailler dans le domaine 0·36–1·2 micron.

(2) Un spectrophotomètre visuel à " Séparateur photométrique"[5] utilisable uniquement à l'étude des lames à faces parallèles non diffusantes.

(c) Pour l'ultra-violet

Un monochromateur double à prismes de Cornu et miroirs, éclairé par un tube ou un arc à fenêtre de quartz, et qui peut être associé :

(1) Soit à un "Amplificateur photoélectrique" spécial pour l'ultra-violet, sensible dans le domaine 0·24–0·6 micron.

(2) Soit au récepteur thermoélectrique décrit plus haut, en utilisant la thermopile compensée de Bayle.

Renvoyant pour plus de détails aux publications indiquées, nous limiterons l'étude ci-après au domaine 0·36–1·2 micron.

2. Photométrie Photoélectrique

L'amplificateur photoélectrique, dont un prototype a été réalisé par Mr. Terrien au Bureau International des Poids et Mesures, est représenté sous sa forme actuelle par la figure 14.1.

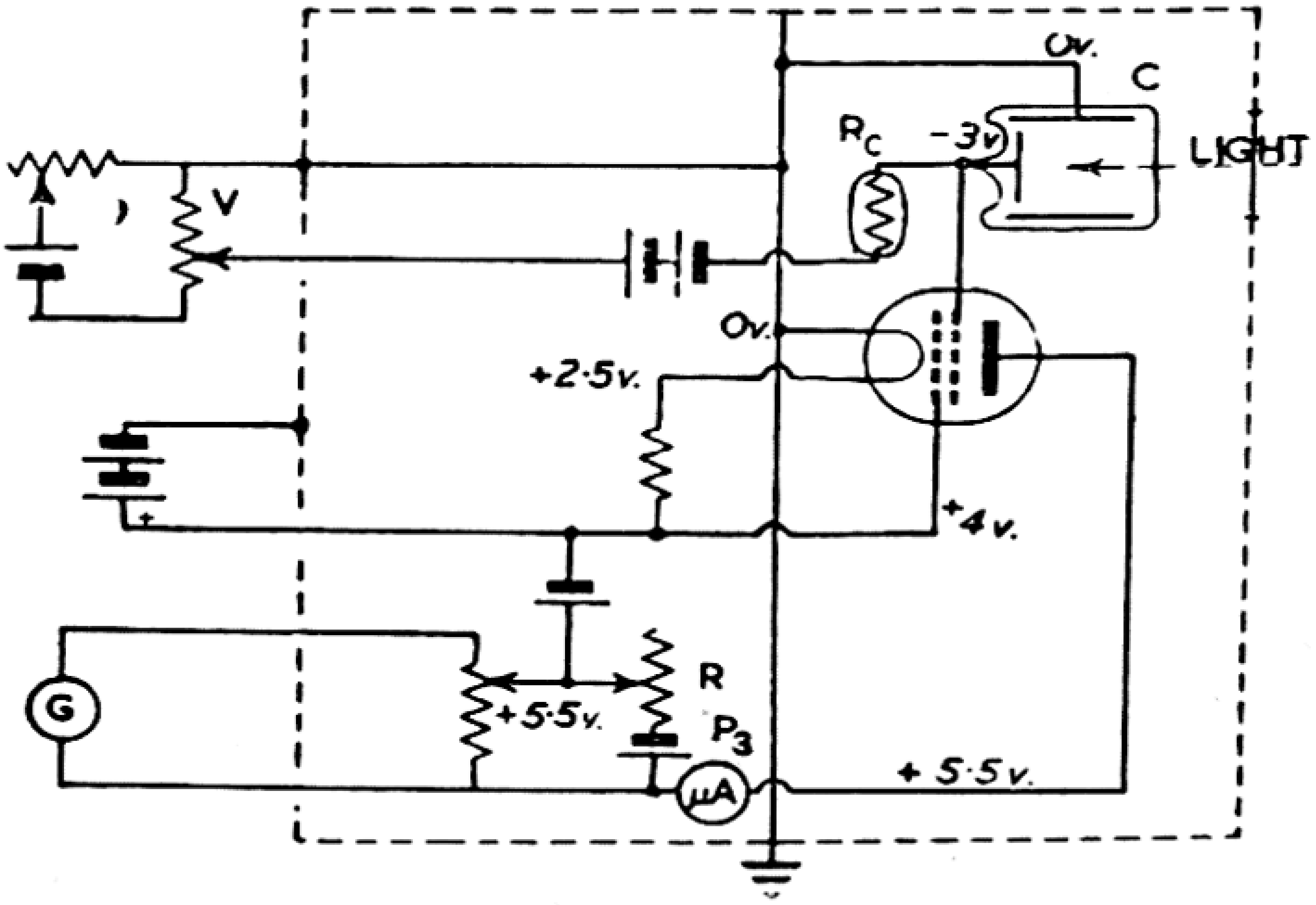

FIG. 14.1. Schéma électrique de l'amplificateur photoélectrique.

Description

C est une cellule Boutry-Gillod[6], au césium sur argent oxydé ; *Rc* est une résistance Vodar[7], de $1{\cdot}3 \times 10^{10}$ ohms, constituée par une couche mince de platine ou de palladium déposée sur une tige de quartz fixée dans un tube de verre vidé, scellé et portant les électrodes. *E* est un tube électromètre tétrode classique. Le courant de plaque de l'électromètre est dérivé dans un circuit comportant une pile P_3 et une résistance R réglée de telle façon que la différence de potentiel aux bornes du galvanomètre G soit nulle lorsque la cellule C n'est pas éclairée et que le potentiomètre V est au zéro. Cellule, électromètre et résistance de couplage sont dans une enceinte mettant ces pièces à l'abri des pertubations électrostatiques et de l'humidité.

Caractéristiques

Nous avons trouvé expérimentalement les caractéristiques suivantes :

Sensibilité, approximativement constante dans le domaine 0·38–1 micron :

— au potentiomètre U : 0·13 volt par erg/seconde

— au galvanomètre G : 2×10^{-6} ampère par erg/seconde.

Fluctuations au galvanomètre G : valeur quadratique moyenne $7 \cdot \times 10^{1\,0}$ ampère, soit 1 mm. sur l'échelle.

Méthodes de mesure, précision et exactitude

(*a*) *Mesure de flux.* La mesure d'un flux lumineux peut être faite en se servant de l'amplificateur comme appareil de zéro et en mesurant la chute de tension dûe au courant photoélectrique dans la résistance Rc par compensation au moyen du potentiomètre V.

Si l'on n'a à mesurer que des rapports de flux, on peut utiliser l'une des deux méthodes suivantes :

(*b*) *Par déviation* : en laissant le potentiomètre au zéro, et en observant les déviations du galvanomètre. Cette méthode permet des mesures rapides ; elle peut assurer, à quelques millièmes près la mesure de rapports de flux voisins de l'unité, et à ± 3/100 près de leur valeur, celle de rapports de flux atteignant 10. L'expérience a montré que, par cette méthode, les erreurs systématiques observées sont dûes, pour la majeure partie, au galvanomètre.

(*c*) *A l'aide du potentiomètre.* Cette méthode, plus lente que la précèdente, permet de mesurer des rapports de flux atteignant 1000 avec une incertitude relative inférieure à ± 2·5/100. Le potentiomètre V est un appareil classique à quatre boites de résistances permettant de mesurer des différences de potentiel atteignant 2 volts par fractions de 0·0001 volt.

La mesure directe de la chute de potentiel dans la résistance de couplage nécessite la manipulation de quatre boutons. Lorsqu'on ne mesure que des rapports de flux, on règle le courant tare de telle façon qu'à une unité de la manette 0·01 corresponde 100 mm. de déviation sur l'échelle du galvanomètre G ; on évite ainsi la manipulation de deux boutons, les deux derniers chiffres étant fournis par déviation.

La Table 1 justifie l'emploi de cette méthode et la précision estimée, elle indique les valeurs trouvées pour la densité optique spectrale de trois verres neutres A, B, C pris d'abord séparément, puis deux à deux, puis ensemble. La comparaison des densités des groupes, calculées à partir des trois premiers résultats ou mesurées directement montre que les écarts observés sont toujours inférieurs aux incertitudes de mesure calculées en admettant une indétermination de ± 0·5 mm. sur la position du spot.

TABLE 1.

Densites optiques de trois verres neutres A, B et C.

λ mμ	400	500	600	800	1000
$\delta\lambda$ mμ	1·1	1·3	1·4	3·3	2·7
A mesuré	0·8875 ±0·0002	0·80815 0·00015	0·83747 0·00015	1·0131 0·0003	1·5131 0·0007
B mesuré	1·1722 0·0004	1·0665 0·0003	1·1062 0·0003	1·3420 0·0005	2·0103 0·002
C mesuré	1·3346 0·0006	1·1637 0·0004	1·1736 0·0004	1·2899 0·0005	1·9161 0·0018
$A+B$ mesuré	2·057 0·004	1·874 0·0017	1·945 0·0017	2·351 0·005	3·539 0·07
$A+B$ calculé	2·0597 0·0006	1·8746 0·0005	1·9437 0·0005	2·3551 0·0008	3·523 0·003
$A+C$ mesuré	2·221 0·005	1·974 0·0025	2·011 0·0025	2·303 0·005	3·443 0·06
$A+C$ calculé	2·2221 0·0008	1·9719 0·0006	2·0110 0·0006	2·3030 0·0008	3·429 0·002
$B+C$ mesuré	2·505 0·01	2·231 0·004	2·280 0·004	2·634 0·009	
$C+B$ calculé	2·5068 0·001	2·2302 0·0007	2·2797 0·0007	2·6318 0·001	3·926 0·004
$A+B+C$ mesuré		3·032 0·025	3·101 0·025	3·57 0·08	
$A+B+C$ calculé	3·394 0·0012	3·0384 0·0009	3·1172 0·0009	3·6449 0·0013	5·439 0·005

3. Monochromateur double

Description et caractéristiques

Cet appareil, dont la figure 14.2 donne le schéma, est à dispersions soustractives : il comporte deux monochromateurs simples symétriques par rapport au plan de la fente médiane F_2. Chacun de ces monochromateurs simples utilise des fentes F_1, F_2 et des miroirs sphériques M_1, M_3 fixes constituant un montage en Z, et un système dispersif de Wadsworth à prisme de flint P et miroir plan M_2 monté sur une plateforme p dont la rotation assure le changement de longueur d'onde.

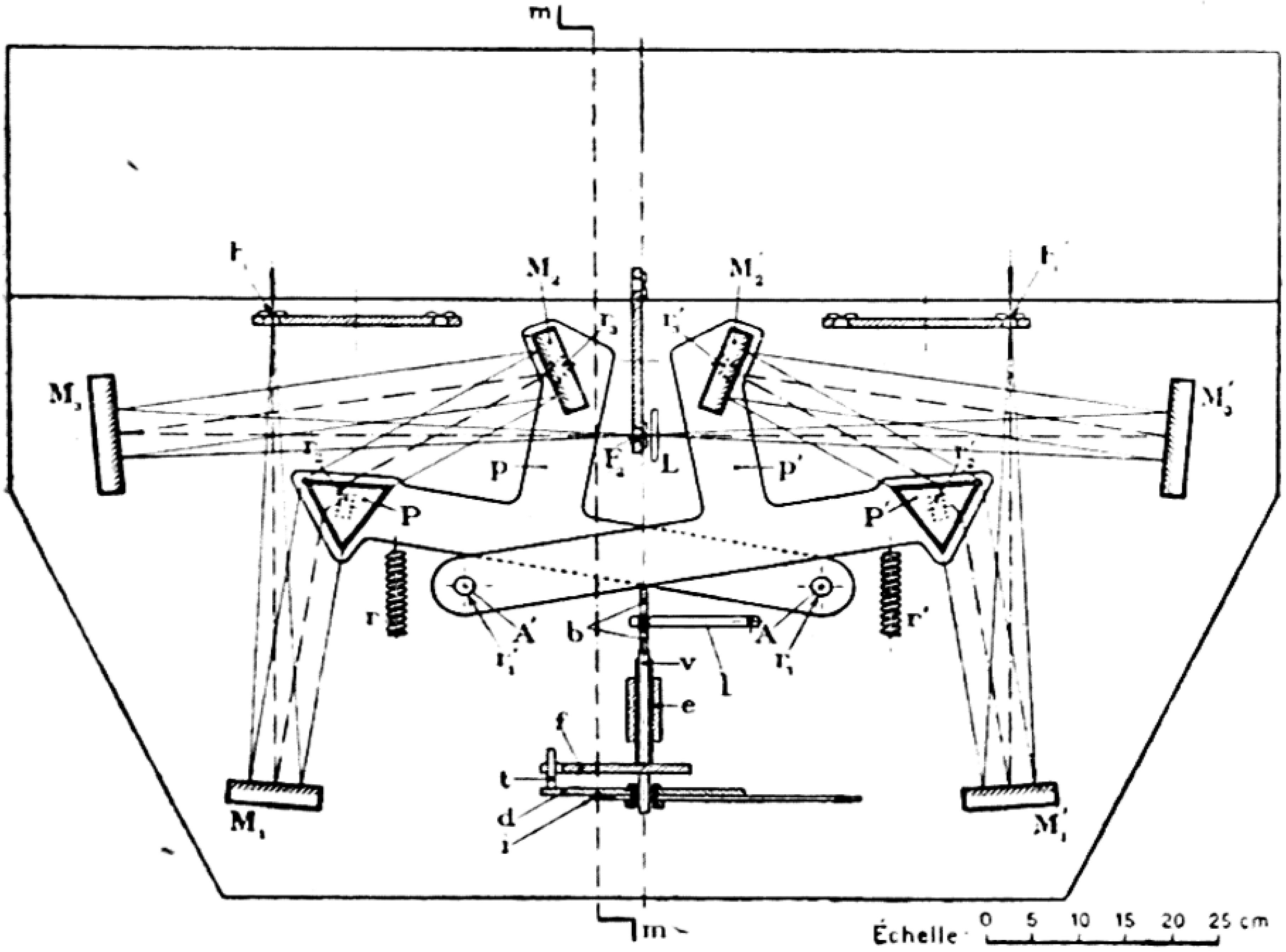

FIG. 14.2. Schéma de monochromateur double.

La disposition de ces éléments a été choisie telle que les aberrations géométriques résultant de l'emploi des miroirs sphériques M_1M_3 perturbent le moins possible la finesse des images des fentes. La calcul des aberrations a fait l'objet d'un travail théorique et expérimental dont seuls les résultats numériques ont été publiés$_3$.

Les diaphragmations en oeil de chat, particulièrement gênantes dans les régions invisibles du spectre ont été réduites au minimum :

(*a*) par l'emploi de miroirs assez grands pour que les prismes et les fentes soient seuls à limiter les faisceaux, (*b*) par l'emploi d'une lentille de champ L qui, avec M_3 et M'_3, conjugue les deux prismes P et P',

(*c*) par le choix de la position des axes de rotation A et A' telle que le déplacement latéral des pupilles résultant de la rotation des plateformes p et p' soit aussi petit que possible.

Grâce à ces précautions, dans le domaine 0·36–2 microns l'angle solide sous lequel on voit la pupille depuis les fentes extrêmes ne varie pas de plus de ± 2%, et la direction de l'axe des faisceaux correspondants ne se déplace pas de plus de 2/1000 de radian de part et d'autre de la direction moyenne.

Le changement de longueur d'onde, résultant de la rotation d'angles égaux mais de sens inverses des plateformes p et p' est assuré par le mécanisme suivant : la rotation donnée par l'opérateur à la manivelle m est transmise par un pignon à un disque denté d portant une rainure en spirale servant de guide à un index i en face duquel on lit la longeur d'onde λ gravée sur le disque. Par l'intermédiaire d'un doigt t fixé au disque, la rotation est transmise à une fourchette f solidaire d'une vis v qui, en tournant dans un écrou fixe e, transforme cette rotation en translation et sert ainsi à pousser les deux plateformes p et p' par l'intermédiaire d'un levier l et de tiges d'acier b à bouts sphériques.

Le réglage de la distance des points d'appui des tiges d'acier b aux axes de rotations A permet d'ajuster la symétrie de l'appareil et d'immobiliser l'image de la fente d'entrée F_1 sur la fente de sortie F'_1 ; cette image ne se déplace pas de plus de 0·02 mm dans le domaine 0·4–0·7 micron.

Reproductibilité d'une longueur d'onde

Grâce à la petitesse des forces de frottement, les axes de rotation des lourdes plateformes p étant définis par les roulements à billes r_1, r_2 et r_3, et à la réduction des jeux par les ressorts de rappel r, le " temps perdu " du mécanisme est petit et l'orientation des plateformes est bien reproductible.

La figure 14.3 représente les résultats d'une expérience faite pour étudier cette reproductibilité : elle donne, en fonction de la longueur d'onde lue sur l'échelle, le flux issu du monochromateur éclairé par un arc à mercure à basse pression, flux mesuré par l'amplificateur photoélectrique. L'expérience a été faite avec des fentes d'entrée et médiane de 0·05, 0·1 et 0·2 mm. de large et par longueurs d'onde lues croissantes, puis décroissantes.

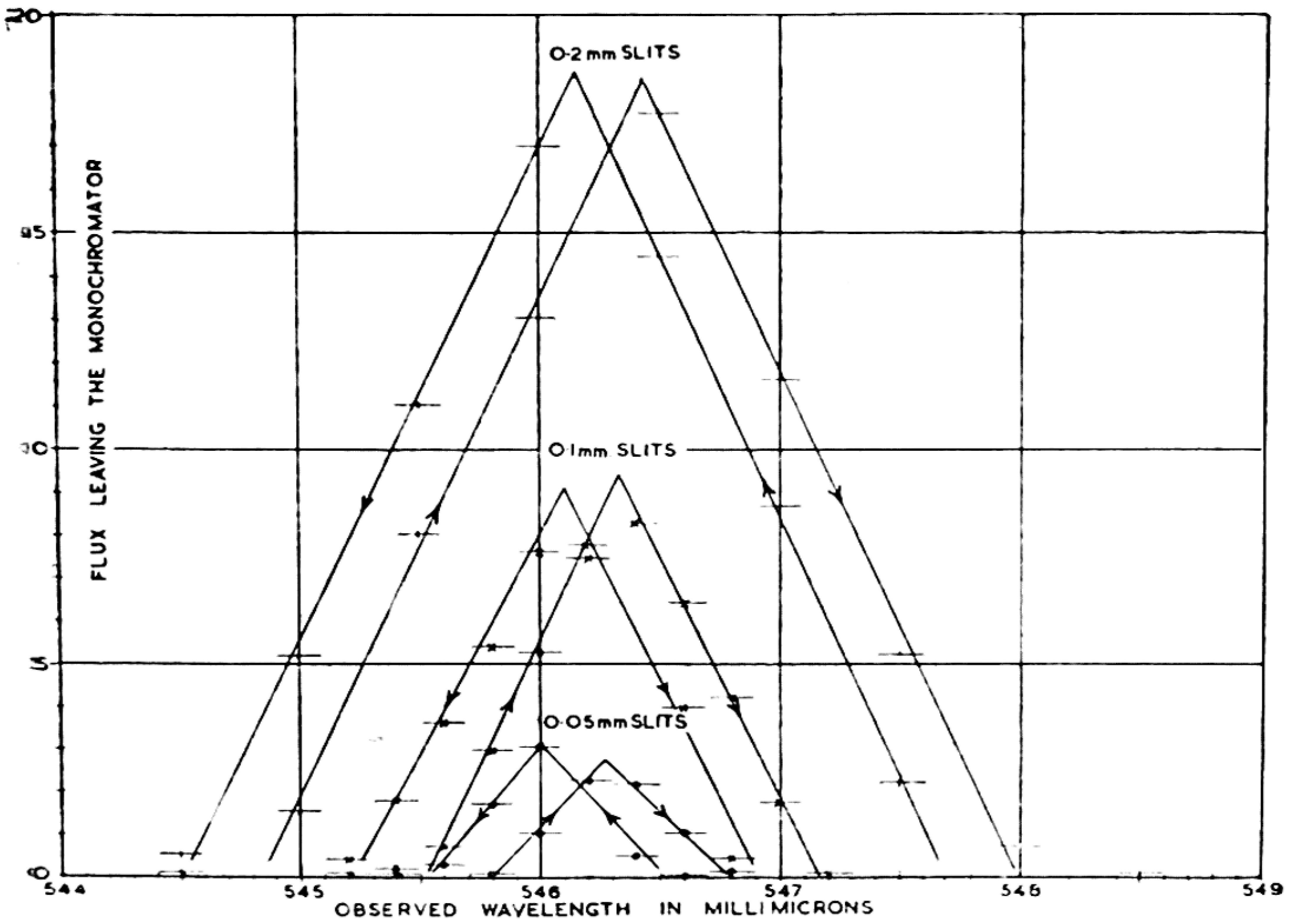

FIG. 14.3. Monochromateur double à prismes de flint et miroirs. Reproductibilité d'une longueur d'onde et " temps perdu. "

Les graphiques montrent que le temps perdu est de 0·2 à 0·3 mμ à 546 mμ, ce qui correspond, sur la vis, à un jeu axial de 4 microns environ. Lorsqu'on reprend la même longueur d'onde en finissant de tourner la commande toujours dans le même sens, la longueur d'onde est reproduite à 0·1 mμ près à 546 mμ, ce qui correspond à l'incertitude de lecture sur l'échelle.

Largeurs de bande

Chacune des trois fentes : entrée F_1, médiane F_2 et sortie F'_1 est choisie, selon le besoin, parmi huit fentes de largeur fixe montées sur un disque muni d'un axe et de butées permettant une mise en place précise. Les largeurs auxquelles ces fentes ont été réglées sont 0·05, 0·1, 0·2, 0·4, 0·7, 1·0, 1·5, et 2·0 mm. Le principal avantage de ce dispositif est de fournir des fentes dont la largeur, bien reproductible, peut être bien connue.

La figure 14.4 représente les résultats d'une expérience permettant d'étudier le centrage des fentes et leur largeur. Le montage est le même que celui rappelé ci-dessus : on mesure toujours le flux issu du monochromateur éclairé par une lampe à mercure, mais en opérant pour diverses largeurs de fente et seulement par longueurs d'onde croissantes.

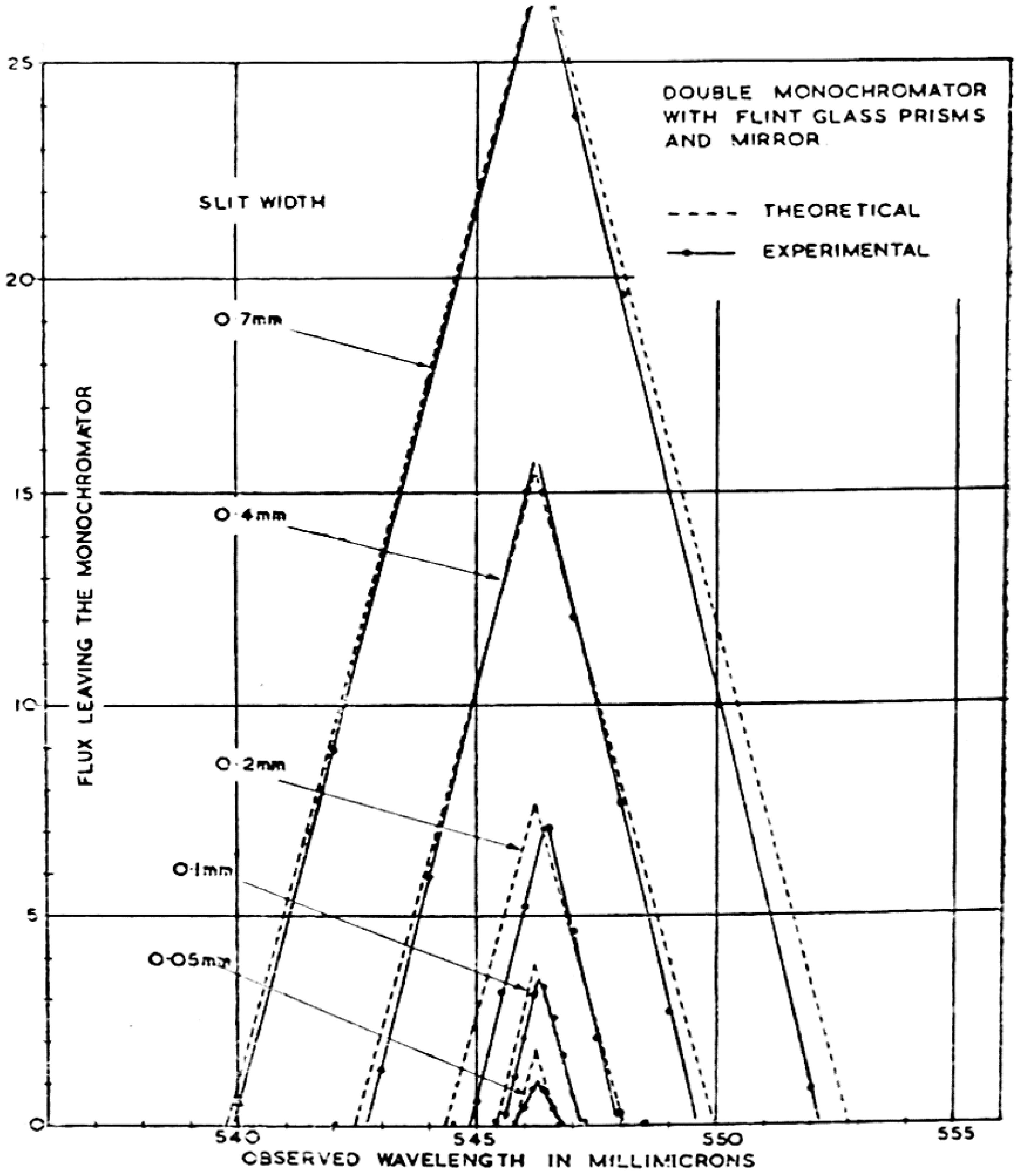

Fig. 14.4. Monochromateur double à prismes de flint et miroirs. Défauts de centrage et de largeur des fentes.

La fente de sortie F'_1 a 2 mm. de large, les fentes d'entrée F_1 et médiane F_2 ont les largeurs indiquées sur les graphiques ; la hauteur utile des trois fentes est 2 mm. Sur ce graphique, les résultats de l'expérience sont représentés par les courbes en traits pleins, alors que ceux de l'instrument théoriquement parfait, au sens que l'on donne à ce terme en optique géométrique, sont représentés par des tirets.

Les bases des triangles théoriques ont été calculées à partir des largeurs attribuées aux fentes et du graphique de dispersion établi au moyen de l'étude du spectre donné par l'instrument ; leurs hauteurs ont été calculées de façon telle que la hauteur au sommet des triangles théorique et expérimental pour les largeurs de fente 0·7 mm. coïncident, les autres hauteurs théoriques étant établies d'après la précédente.

L'écart maximum de longueur d'onde moyenne est de 0·2 mμ à 546 mμ, soit un défaut de centrage des fentes de 0·02 mm. ; la plus grande erreur de largeur de bande est de l'ordre de 0·5 mμ, soit un décalage d'une lèvre de 0·05 mm. Ces écarts ne sont pa seulement attribuables au règlage des fentes, mais encore aux jeux du mécanisme des disques-porte fentes et aux défauts de profil des lèvres.

La différence de hauteur entre les triangles expérimentaux et théoriques, de plus en plus importante au fur et à mesure que la largeur des fentes diminue, est attribuable, d'une part aux imperfections des fentes, et d'autre part aux défauts des images optiques (l'ouverture relative du monochromateur étant f/9, la largeur de la tache centrale de diffraction pour l'instrument parfait serait voisine de 0·01 mm).

Nous avons étudié sommairement l'influence de la hauteur des fentes sur les caractères de la bande spectrale transmise ; avec des fentes de 0·05 mm. de large, lorsque la hauteur passe de 2 mm. environ à 30 mm., la hauteur du triangle expérimental n'est multipliée que par 9, la largeur de la bande passe de 0·50 à 0·62 mμ (à 546 mμ) et la longueur d'onde moyenne est décalée de 0·1 mμ au plus. La rapport des aires des triangles expérimentaux, qui devrait être égal au rapport des hauteurs de fente est de 11. Qualitativement, ces faits sont en accord avec les calculs montrant l'influence de l'astigmatisme des miroirs sphériques sur la qualité des images.

Une longueur d'onde moyenne est donc reproductible à ± 0·2 mμ près environ à 546 mμ. Si l'on admet que ces défauts de reproductibilité ne sont dus qu'à des causes mécaniques indépendantes de la région du spectre, et par conséquent qu'ils correspondent à 0·02 mm. dans le plan des fentes, ces défauts atteignent ± 0·5 mμ à 700 mμ ; ± 0·7 à 800 ; ± 1·1 à 1000 ; ± 2 à 1400 et ± 3 à 1800.

Etalonnage en longueurs d'onde

La méthode suivante[8] permet de réduire considérablement les erreurs d'interpolation. Un arc à mercure du type Philips HP 300 fournit des repères assez sûrs et assez intenses pour que l'incertitude sur leur position dans l'échelle ne dépasse guère les défauts de reproductibilité ; ce sont notamment les raies 404·7, 407·7, 435·8, 491·6, 546·1, 576·9, 579·1, 690·7, 1014·0 et 1128·7 mμ. Un étalonnage sommaire étant fait au moyen de ces raies, on repère sur l'échelle des longueurs d'onde et dans tout le domaine spectral du monochromateur, soit de 0·36 à 1·9 micron, la position de toutes les fines bandes de transparence d'un étalon interférentiel de Fabry et Pérot dont l'épaisseur de la lame d'air est de l'ordre de 0·01 à 0·02 mm. En choisissant deux bandes voisines de deux raies repères et au moyen de leurs différences d'ordre d'interférence et de leurs longueurs d'onde (calculée avec une précision suffisante grâce à l'étalonnage sommaire précédent), on calcule l'épaisseur de l'étalon et les ordres de chacune des cannelures, donc les longueurs d'onde correspondantes, ce qui fournit une cinquantaine de repères précis répartis régulièrement dans tout le spectre. Le calcul des ordres d'interférence et de l'épaisseur de la lame d'air étant généralement fait avec des cannelures voisines de 546·1 et 1014·0 mμ, les autres raies de mercure permettent un contrôle des résultats.

Cette méthode d'inter et d'extrapolation par un procédé physique nous permet d'assurer l'exactitude des longueurs d'onde à $\pm$ 1 mμ près à 700 mμ, $\pm$ 2 à 900 mμ, $\pm$ 4 à 1300 et de $\pm$ 8 à 1900.

Influence de la température sur l'étalonnage

La longueur d'onde transmise diminue quand la température s'élève. Les graphiques de la figure 14.5 représentent les différences observées, pour les raies visibles du mercure, entre la longueur d'onde vraie transmise et la longueur d'onde lue, en fonction de la température, de 11 à 28° C. D'après ces mesures et dans le domaine où elles sont valables, tout se passe comme si le spectre donné par le premier monochromateur se déplaçait sur la fente médiane de (14·5 $\pm$ 2) microns pour une élévation de température de 1° C., indépendamment de la région spectrale. Un étalonnage établi à la température T ne reste donc valable, à l'incertitude estimée près, que dans le domaine $(T-3)$ à $(T+3)$ °C.

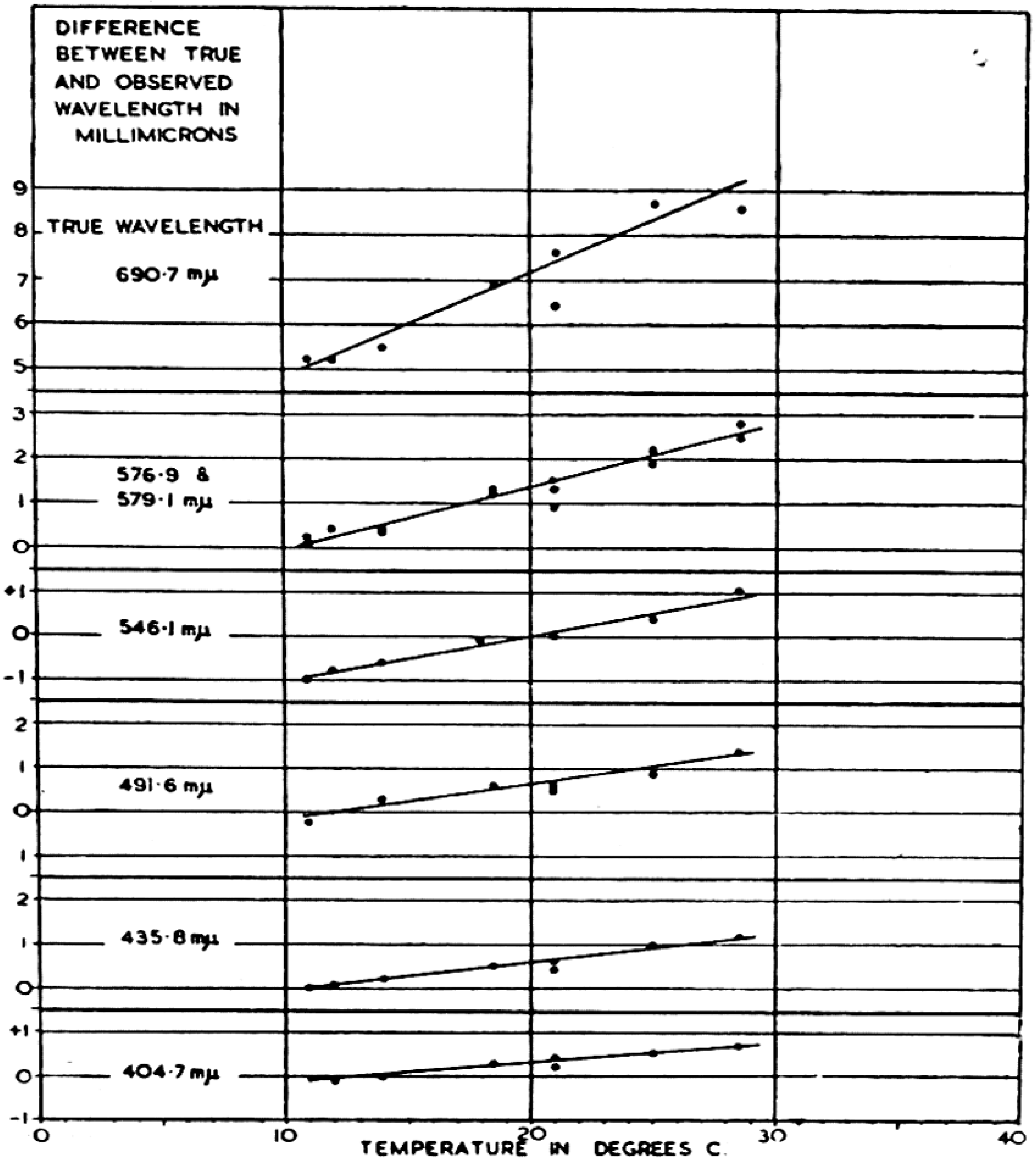

Fig. 14.5. Monochromateur double. Influence de la température sur l'étalonnage.

Lumière parasite

Afin de nous assurer que la lumière parasite sortant du monochromateur ne peut pas fausser les mesures, nous avons déterminé séparément et par combinaison les densités optiques de deux verres au didyme aux maxima de densité. Cette expérience est très probante car la transparence globale de ces verres pour la source et le récepteur utilisé est très élevée (supérieure à 50%) et les bandes d'absorption sont à la fois trés ètroites et très marquées.

Le tableau 2 représente les résultats obtenus. Ici encore, les incertitudes indiquées sont calculées en admettant une indétermination de ± 0·5 mm. sur la position du spot. On remarquera notamment que les mesures faites à 582 mμ, avec des fentes d'entrée et médiane de 0·1 mm. de large définissant la bande spectrale, ne sont pratiquement pas affectées par la largeur de la fente de sortie qui, ici, a pour unique rôle d'arrêter la lumière parasite.

TABLE 2.

Densites optiques de deux verres au didyme D et E aux minima des courbes de transparence spectrale.

λ	Largeurs des fentes en mm.			δλ	Densités optiques			
mμ	*e*	*m*	*s*	*mμ*	*D* mesuré	*E* mesuré	*D*+*E* calculé	*D*±*E* mesuré
528	0·1	0·1	0·2	0·80	1·0006 ±0·0004	1·900 0·003	2·901 0·003	2·895 0·03
528	0·1	0·1	0·4	0·80	1·0042 0·0005	1·896 0·004	2·900 0·005	2·902 0·04
528	0·1	0·1	1·5	0·80	1·0041 0·0005	1·902 0·004	2·906 0·005	2·899 0·04
513	0·05	0·05	1·5	0·37	0·6378 0·001	1·196 0·003	1·833 0·004	1·833 0·01
513	0·1	0·1	1·5	0·74	0·6368 0·0002	1·1931 0·0007	1·8299 0·0009	1·830 0·003
881	0·05	0·05	0·4	2·1	0·8253 0·0003	1·554 0·002	2·379 0·002	2·364 0·006

4. Sources de lumière

Lorsqu'on ne désire pas faire de mesures énergétiques, la source de lumière la plus couramment employée est une lampe à filament de tungstène hélicoïdal 12 volts, 3 ampères alimentée par des accumulateurs et portée à la température de 2900° K. La sensibilité du montage est alors suffisante pour qu'on puisse mesurer des densités optiques de 3 à ± 0·02 près avec des bandes spectrales dont les largeurs δλ sont les suivantes :

à λ mμ ...	360	400	500	600	800	1000
δλ mμ ...	3	1	1·5	3	3	3

Si l'on place entre le monochromateur et le photomètre un réflectomètre absolu selon Taylor dont la sphère a un diamètre de 50 cm. et dont la peinture intérieure a un facteur de réflexion de 0·8, on parvient à mesurer des facteurs de réflexion absolus à ± 0·01 près avec des bandes spectrales dix fois plus larges que ci-dessus.

Lorsque nous mesurons les facteurs de transmission ou de réflexion de surfaces, de matériaux ou d'instruments optiques (lentilles, miroirs non plans, objectifs, viseurs, . . .) qui modifient sensiblement les trajets des rayons lumineux, nous plaçons l'échantillon entre la fente d'entrée et une source à luminance uniforme[9] constituée par un verre opalin plaqué contre l'ouverture d'une sphére creuse contenant une lampe à incandescence (12V, 3A, 2900° K) et dont les parois sont recouvertes d'une peinture blanche résistant à la chaleur. La luminance du plan est de l'ordre de 3 stilbs ; sur une surface circulaire de diamètre utile 16 mm., cette luminance est uniforme à ± 2% près. Cette source permet de mesurer des facteurs de transmission et de réflexion superieurs à 0·1 avec une incertitude relative inférieure à ± 2% avec des bandes spectrales dont les largeurs $\delta\lambda$ sont :

à λ mμ ...	400	500	600	800	1000
$\delta\lambda$ mμ ...	2	1·5	1·5	2	3

Lorsque les contacts aux 24 bornes des accumulateurs sont propres, les fluctuations de l'intensité lumineuse des lampes, en dehors de toute dérive régulière, sont de l'ordre de 3/10,000.

5. Spectrophotométrie visuelle

Pour mesurer la densité optique de lames à faces planes, et parallèles non diffusantes, nous disposons d'un spectrophotomètre visuel que nous avons étudié avec M. Terrien d'après un schéma original de M. Fleury.

Dans cet instrument, le monochromateur double est complètement séparé du photomètre : nous ne parlerons que de ce dernier qui est en service depuis septembre 1945.

Description

Le "Séparateur photométrique" (Fig. 14.6) utilise une méthode de substitution : la densité optique de l'échantillon *E* est mesurée par comparaison à celles d'un disque de Talbot *T* à densités fixes, l'interpolation entre les densités du disque étant faite à l'aide d'un coin photométrique *C* en verre neutre. Un objectif collimateur *O* donne de la fente de sortie *F* du monochromateur double une image à l'infini ; la lumière traverse une lame de verre *S* à faces planes et parallèles nues, oblique, donnant :

(1) par réflexion un faisceau tare traversant un système optique dont la transparence, réglée avec des densités *N* de verre neutre, ne sera pas modifiée au cours des mesures.

(2) par transmission, un faisceau mesure qui traverse le coin *C*, son contre coin *C'*, l'échantillon *E* et le disque de Talbot *T*.

A l'aide d'un oculaire *O'*, qui forme de la fente d'entrée *F* une image sur la pupille de l'observateur, celui-ci compare les luminances des faisceaux qui se rejoignent sur le cube photométrique *P*.

Les densités optiques du disque *T* sont déduites des mesures des angles d'ouverture des secteurs par application de la loi de Talbot. La pente du coin *C* est déterminée par substitution des densités du coin à celles du disque. Enfin la densité d'un échantillon est mesurée en la remplaçant par la densité du disque la plus voisine et par un appoint fourni par le coin.

Précédé d'un monochromateur double de Van Cittert éclairé par une lampe à incandescence (température de couleur 2·900° K) ; ce photomètre permet de mesurer des densités optiques de 2 en employant les bandes spectrales $\delta\lambda$ suivantes :

à λ mμ ...	400	450	500	550	600	650	700
$\delta\lambda$ mμ ...	15	10	5	3	5	10	15

Tant que la brillance du champ n'est pas inférieure à un niveau correspondant aux conditions ci-dessus, l'incertitude sur la densité optique n'est pas supérieure à ± 0·01, sauf dans le violet.

L'emploi d'un monochromateur mieux adapté à ce photomètre, en ce qui concerne l'ouverture (f/12), notamment, permettrait de diviser la largeur des bandes spectrales par 3 ou 4 sans que le monochromateur soit de dimensions excessives.

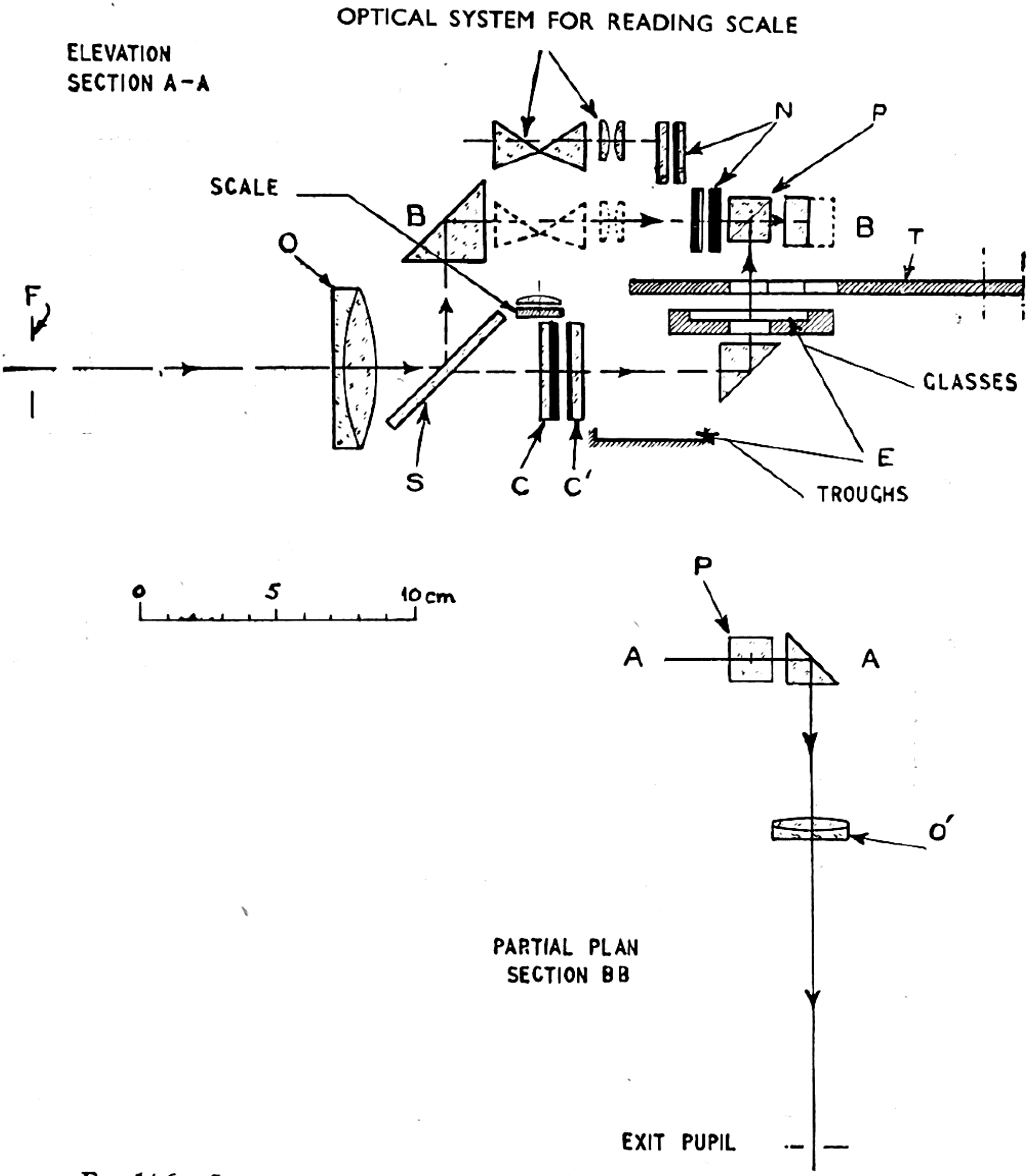

FIG. 14.6. Separateur photometrique utilisant une methode de substitution.

Dans le domaine où cet appareil est utilisable (densité maximum mesurable directement : 3), aucune erreur systématique non attribuable aux effets de largeur de bande n'a été observée. La figure 14.7 donne un exemple de comparaison de résultats de mesures faites par les méthodes photoélectrique, visuelle et thermoélectrique.

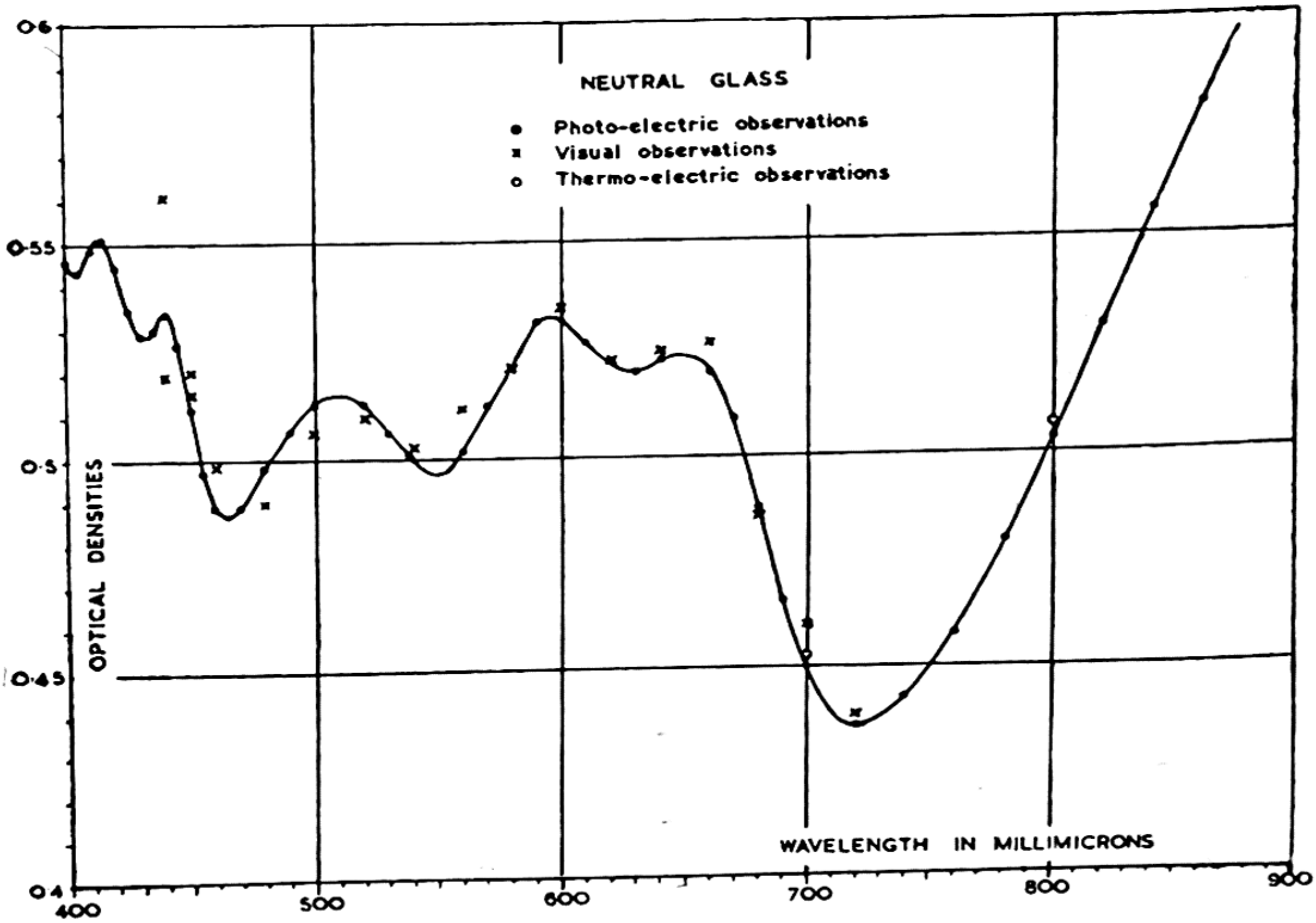

FIG. 14.7. Verre neutrale. Comparaison de résultats de mesures de densité contre la longeur d'ondes.

6. Conclusions

En ce qui concerne notre équipement pour le spectre visible, les incertitudes sur la longueur d'onde sont généralement plus gênantes que les incertitudes sur la mesure photométrique, particulièrement pour les filtres colorés où la densité optique varie très vite avec la longueur d'onde. Il nous semble que le premier progrès à faire concerne le monochromateur qui devra être peu ouvert, afin que les images soient de bonne qualité, et très dispersif afin que les imperfections des fentes aient les conséquences les plus faibles possible. La conservation de l'étalonnage en longueurs d'onde est difficile à obtenir avec les monochromateurs à miroirs, en raison de l'importance capitale de la stabilité mécanique de l'instrument : c'est un problème que nous cherchons à résoudre.

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SOMMAIRE

SUMMARY

Sources de lumiére (notamment plans à luminance uniforme) ; alimentation ; caractéristiques : dimensions, stabilité, luminance.

Monochromateur double à miroirs :
- Caractéristiques géométriques et spectrales.
- Lumière parasite : résultats expérimentaux.
- Etalonnages en longeur d'onde :
  - méthodes employées, leur précision.
  - influence de la température, stabilité dans le temps
  - influence des largeurs de fente,
  - reproductibilité d'une longueur d'onde.

Largeurs de bande : comparaison des valeurs expérimentales et théoriques.

Mesures visuelles :
- Description du " Séparateur photométrique " et de la méthode de mesure.
- Densités optiques maxima mesurables en fonction de la longueur d'onde et de la largeur de bande.
- Précision.

Mesures photoélectriques.
- Description de " l'Amplificateur photoélectrique " et de la méthode de mesure.
- Caractéristiques : stabilité, sensibilité, proportionnalité.
- Précision:

Mesures thermoélectriques.

Exemples de résultats.

SUMMARY

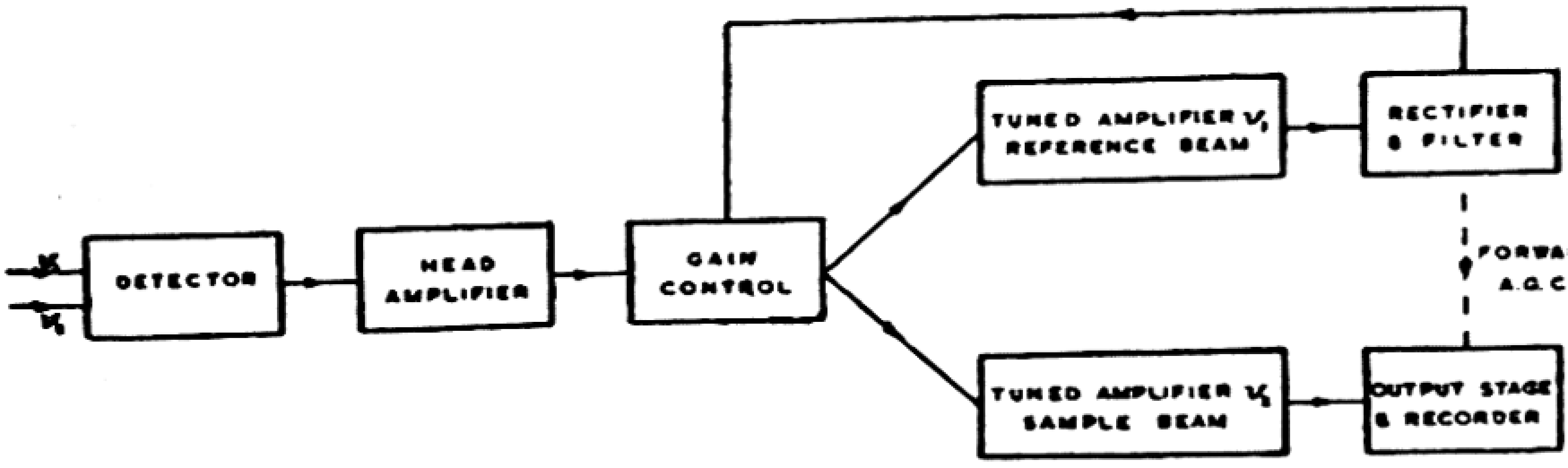
This paper describes the equipment available for spectrophotometric work at the Institute, including a photoelectric amplifier employing an electrometer tetrode. A full description is given of a double monochromator and its characteristics.

The effects of centring faults, slit width, and temperature have been investigated and the results are shown graphically. A brief description of the light sources used is followed by an account of a visual spectrophotometer utilising the substitution method. The problems of immediate interest to the author are improvements in the monochromator for mechanical stability to give greater constancy of calibration.

DISCUSSION ON SPECTROPHOTOMETER SYMPOSIUM

Professor A. M. Taylor. "I wish to bring to the notice of the Conference a new type of double beam spectrophotometer due chiefly to P. D. Fochs in the Physics Laboratory at Southampton. This is based on well known electronic methods and the principle may be applied to most spectrometers. The prototype was rigged up in the spring of 1949 but pressure of other work delayed the completion of the circuitry until recently.

"The arrangement is shown in the block diagram. Two beams external to the spectrometer are used, one the reference beam and the other the sample beam in which absorption or reflectance is to be measured ; these two are combined before entering the slit of the spectrometer and after traversing the optical system, fall together on the same receiver. The beams are earmarked by being chopped at some convenient point before entry, the reference beam at a frequency ″° and the sample beam at a frequency ″°. The choice of these frequencies depends partly on the characteristics of the receiver and partly on the subsequent circuitry ; we are using a fast Schwarz thermopile (sensitivity 80 microvolts per microwatt) and are at present chopping the beams at 5 and 22 c/s respectively. In the visible region we have substituted a photocell for the thermopile, but the chopping frequencies might well have been vastly increased with such a fast receiver. This would have enabled faster scanning of the spectrum.



THE A.G.C. RATIO RECORDING SYSTEM

"The output from the receiver is fed to a head-amplifier stage, then through a special gain control stage and thence to two selective amplifiers in parallel (in our case these are each two-stage, twin-T, negative feed-back amplifiers) which are tuned respectively to ν_1 and ν_2. The output from the amplifier tuned to ν_1 is rectified, filtered and fed back to the gain control stage ; this in effect provides delayed automatic gain control so that the output is, within the limits of this system, constant and independent of the input level of the beam chopped at frequency ν_1. As the output from the selective amplifier tuned to ν_2 is also controlled by the A.G.C. acting on the common gain control stage, this output is, within the limitations of the system, independent of the incident energy and depends only on the ratio of the energy in the beam under measurement, to that in the reference beam. To remove the limitation of the delayed A.G.C., forward A.G.C. is applied to a stage of amplification of the output at frequency ν_2. The output of ν_2 is fed to a pen-recorder, and the chart indicates directly the percentage transmission (or the reflectance) of the sample under measurement.

"Obviously the performance will be dependent on the speed of response of the various parts of the system. It may be noted that it does not appear necessary for the two tuned amplifiers to have identical response times. This would not be the case in any arrangement using a two channel amplifier with the two outputs fed directly to a ratiometer or an electronic ratio recorder. Our instrument has only been in operation for the past two weeks and as soon as measurements are completed a more detailed account will be published."

Dr. Mary P. Lord stated that the measurement of spectral distributions when lines and continua were present together seemed to be of some significance, because the spectra of the majority of fluorescent lamps consisted of lines (mainly those of mercury) superimposed on phosphor continua. Considering the problem for the specific case[1] of a double monochromator, in which the dispersion in the two halves was in the same direction, when used in conjunction with a selective detector it could be assumed that the slits were sufficiently wide for diffraction effects to be negligible and sufficiently narrow for the energy ($E\lambda$) of continuum unit wavelength in the wavelength range $\lambda-(\lambda+d\lambda)$ to be constant over the range of wavelengths embraced by the slits. The following formula can then be derived :—

$$\Sigma\lambda=(E\lambda'-E\lambda).\quad j(s_1, s_2, s_3, \phi\lambda)/s,$$

in which s_1, s_2, s_3 are the widths of the entrance, middle, and exit slits of the monochromator respectively; the width of the narrowest of these slits$=s$, $\phi\lambda$ is the reciprocal of the linear dispersion of either half of the monochromator at wavelength λ, and $\Sigma\lambda$ is the energy of line of wavelength λ emitted by the source. It is supposed that for the values of s_1, s_2 and s_3 actually used, for each wavelength setting of the monochromator, calibration curves of $E\lambda$ *v.* detector response are available (in general, obtained from a grey body radiator).

$E\lambda'$ is the value of $E\lambda$ obtained from the calibration curve, for the detector response given by the line and continuum together.

Expressions [1] for j for various conditions have been derived. It appeared that such considerations were not taken into account in practical spectrophotometry and it would be interesting to have the Conference's comments on this point.

Mr. R. Donaldson said that in measurements made on fluorescent lamps at the N.P.L. the line and continua contributions to the energy curve were distinguished by joining the continuum energy curve across the base of the vertical strips corresponding to the live energy. This gave colour co-ordinates in good agreement with those obtained by other methods. **Dr. Lord** pointed out that this agreement might arise because the line energy was very different from 50 per cent. of the total energy.

Professor A. M. Taylor believed that a paper by Hardy and Young[2] dealt with the problem in detail.

Subsequent note by **Dr. Lord**. This paper and a more recent one are concerned only with the problem of the accurate determination of the spectral transmittance of a substance whose absorption is smoothly continuous.

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A paper on:

Modern Spectrophotometers

was also read at this Session, by **Dr. H. W. Thompson** (St. John's College, Oxford, Gt. Britain), but the material was not available for publication at the time of going to press.

REFLECTING TELESCOPES

15. The Modern Reflecting Telescope

E. H. LINFOOT
(The Observatories, Cambridge, Great Britain)

During the last fifty years, two main trends have been predominant in astronomical telescope design. The one which has attracted most general attention is the great increase in size. The 60-inch Newtonian made and used by Common at Ealing in 1890 was followed by the 60-inch Hooker telescope, erected 18 years later at Mount Wilson, by the 100-inch telescope which came into operation there in 1917, and by the 200-inch Hale telescope which last year began its work on Mount Palomar with such conspicuous success. In such telescopes, the difficulties to be overcome are of a practical rather than a theoretical nature. For example, it is very difficult to cast and anneal the glass discs from which the main mirrors of large telescopes are made. Even if such a disc is available, the task of working it optically to a parabolic figure with an error of about one millionth of an inch is one of great difficulty. Only a very few men living in the world at the present time are capable of producing a 100-inch paraboloidal mirror of this standard of accuracy. When the mirror is finished, it has to be mounted with extreme care on a large number of specially designed, delicately counterpoised supports in order to reduce the distortion inflicted upon it by its own weight. Before it can be used, its surface must be coated evenly with aluminium, evaporated on to it in vacuo, and this alone is a considerable technical feat in the case of a 100-inch mirror. Finally, the distorting effects on the mirror of rising and falling temperatures have to be minimised as far as possible by thermal shielding of the edges of the mirror and by designing the support system to allow free circulation of air round the back of the mirror. These precautions are helpful, but in spite of many efforts, no satisfactory way out of the temperature troubles of large telescope mirrors has yet been found.

Newtonian telescopes suffer the disadvantage in that the images deteriorate rapidly as we move away from the centre of the field. Only by the addition of more optical surfaces can this difficulty be overcome, and from what has been said already it will be clear that many other considerations besides those of theoretical optical performance will play a part in deciding whether a given telescope design is a good or a bad one. No one but a working astronomer is really qualified to pass judgment on a telescope design, and few astronomers have a sufficiently strong interest in optics to wish to experiment with new ideas in this field. It is only once or twice in a century that the average observatory can raise the money to invest in a new large telescope, and it is hard to blame a director who may have had to endure years of heartbreaking negotiation in order to obtain an endowment if, once the funds become available, he prefers to spend them on something that he knows a good deal about already. Nevertheless, this attitude has had unfortunate consequences in the past, It resulted, for example, in the almost complete neglect of the two-mirror aplanat telescopes proposed by K. Schwarzschild in 1905, and rediscovered in a somewhat different form by Ritchey and Chrétien in 1923. These two-mirror systems are now more or less superseded by the Schmidt camera and its later developments, so that Schwarzschild's designs appear to have been put into practice in only two actual telescopes; one, of 24 inches' aperture, at the University of Indiana and the other, of 12 inches' aperture, at Brown University, U.S.A.

A more cheerful history attaches to the brilliantly successful optical design conceived, made and put into use early in 1930 by Bernhard Schmidt at the Bergedorf Observatory, near Hamburg. Schmidt was an astronomical mirror maker of superlative skill, and after spending some years in making mirrors privately for amateur and professional astronomers in Germany, he was persuaded by Schorr in 1926 to join in the work of the Bergedorf Observatory. From the beginning of his residence there, Schmidt was thinking about the problem of improving the off-axis images in reflecting telescopes. It is on record that he spent much time at this period roaming the woods round Bergedorf and talking to himself. Fortunately for optics, no one attempted to interfere with these activities.

In the Spring of 1929, Schmidt went with Baade on an eclipse expedition to the Phillipines, and one evening in the Indian Ocean told him that he had solved the problem of designing a coma-free reflector of large aperture and large field. The design was what is now known as the Schmidt camera, and the first model was completed by Schmidt and put into operation early in 1930. This camera, working at f/1·75, had an aperture of 14 inches and a focal length of 24 inches. It is still in use at Bergedorf and gives beautifully sharp photographs over its curved field of 16° angular diameter. The design is too well-known to need a detailed description here; I will only remind you of the basic idea, which is the correction of the aberrations of a spherical mirror by means of a thin, nearly plane-parallel corrector plate placed in an aperture stop at the centre of curvature of the mirror. (See Fig. 15.1).

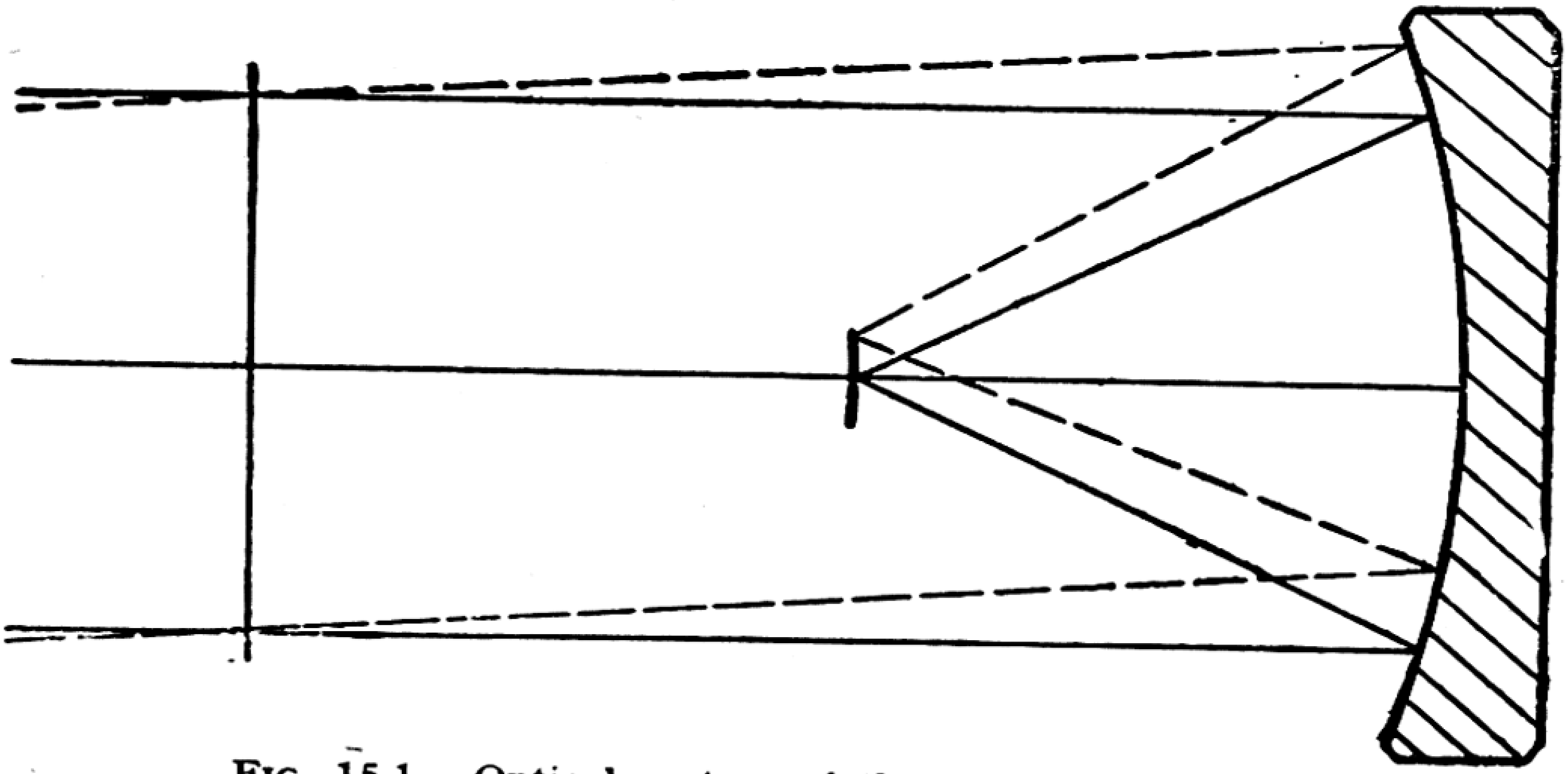

FIG. 15.1. Optical system of the Schmidt telescope.

Schmidt died in 1935 and his discovery was neglected in Europe, but the Californian astronomers, stimulated by Baade, took up the idea with characteristic energy. The Mount Palomar Schmidt, an f/2·5 system working over a 7° field, is the latest successful result of their skill and enterprise in this field.

The optical design of the Schmidt camera involves the user in certain practical inconveniences. In the first place, the overall length of the telescope is twice its focal length, or even more if we include dewcap and mirror-cell. Secondly, the focal surface is inconveniently situated midway between corrector plate and mirror.

Thirdly, the focal surface is not flat but spherical, being concentric with the mirror surface in Seidel approximation.

In large systems used for astronomical research, these drawbacks are not as serious as might at first appear. That of the curved focal surface, for example, can be dealt with by using specially thin glass for the photographic plates and bending them to the correct curvature against a spherical backing plate. On removal from the holder, the plates spring flat again. In the 48–72-inch Palomar Schmidt telescope, square plates as large as 14 inches by 14 inches are successfully treated in this way.

Again, the position of the focal surface is an inconvenience, but there is plenty of room for the observer to reach his arm in to get at the plate holder*, and only the problem of guiding is made more complicated by its rather inaccessible position.

The large overall length is perhaps a more serious matter for the astronomer wishing to instal a large Schmidt telescope, since it considerably increases the cost of the dome or turret which the instrument requires for efficient working.

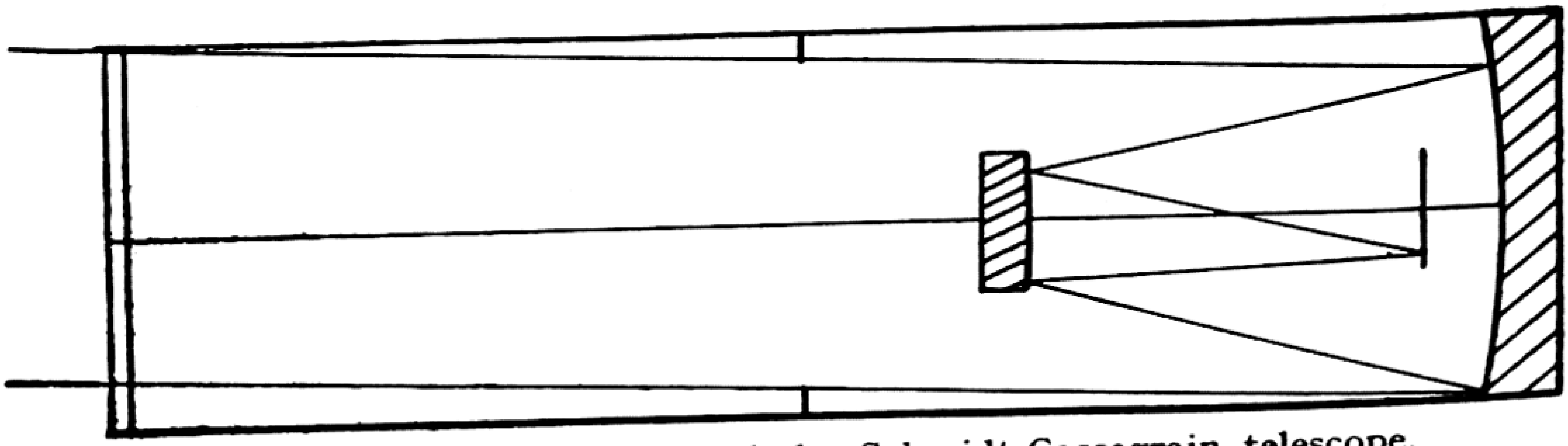

FIG. 15.2. Optical system of the Schmidt-Cassegrain telescope.

It is therefore natural to ask whether some of these drawbacks can be got rid of, without too much loss of theoretical performance, by modifying the optical design, and in 1940 Dr. J. G. Baker published a paper in the *Proceedings of the American Philosophical Society* in which he showed how the field could be flattened and the ratio of overall length to focal length of the system improved by adding a convex secondary mirror to the system. See Fig. 15.2. The same idea was independently suggested by Dr. Burch in a paper in the Monthly Notices of the Royal Astronomical Society in 1942, and also, though in a less general form, by H. Slevogt in the *Zeit-*

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* In several of the large American Schmidt telescopes, mechanical devices bring the plate-holder to the side of the tube after the exposure is completed.

schrift für Instrumentenkunde in the same year. Systems similar to Slevogt's, in which both mirrors are spherical, had also been suggested by me in the same year.

In Baker's and Burch's systems, one or both of the mirrors are usually aspherical as well as the corrector plate, and Baker, in his otherwise valuable book "Telescopes and Accessories", written jointly with Dimitroff, appears to believe that the use of two spherical mirrors involves a big loss in performance. But in fact the off-axis astigmatism which necessarily appears when two spherical mirrors are used is so small that it is comparable with the fifth-order aberrations of the system, and the question whether the practical performance is impaired by restricting both mirrors to be spherical will probably have to be decided by the experience of astronomers on the telescopes now under construction for the St. Andrews Observatory and the Armagh-Harvard-Dunsink Observing station at Blomfontein.

The St. Andrews telescope project was started in 1946, when it was decided to equip the observatory there with a 30–38 inch Schmidt-Cassegrain telescope, to be made in the Observatory workshop as part of a research project under the direction of Professor Finlay-Freundlich. I was asked to undertake the optical design. Because of the novelty of the design, we thought it wisest to begin with the construction of a half-scale pilot model, and it is this pilot model which has recently been mounted and put into operation at the Mills Observatory in Dundee. The intention is to use this pilot model to gain experience of the good and bad qualities of the system under actual observing conditions, and also to train observers in its use while the main model is being built.

The whole of the constructional work, both optical and mechanical, is being done under the direction of Mr. Robert Waland, whose first task when he joined the Department of Astronomy at St. Andrews University in 1946 was to build up optical and mechanical workshops capable of handling a job of this size. Figs. 15.3 to 15.6 will give some idea of the success which his zeal and energy have commanded.

The Isaac Newton Telescope

As you may know, it has been decided to construct a new large telescope in this country, to be located at Herstmonceux in Sussex, near the new site of Greenwich Observatory. The optical design of this telescope is in some ways unusual. It has been decided to make it a Schmidt camera of 300 inches focal length, which can be converted for spectroscopic purposes by removing the corrector plate and using a heavily figured Gregorian secondary mirror M_2 to compensate the spherical aberration of the 98-inch spherical primary mirror. See Fig. 15.7. The light returning from the secondary may then be sent up to the north end of the polar axis by means of a diagonal flat

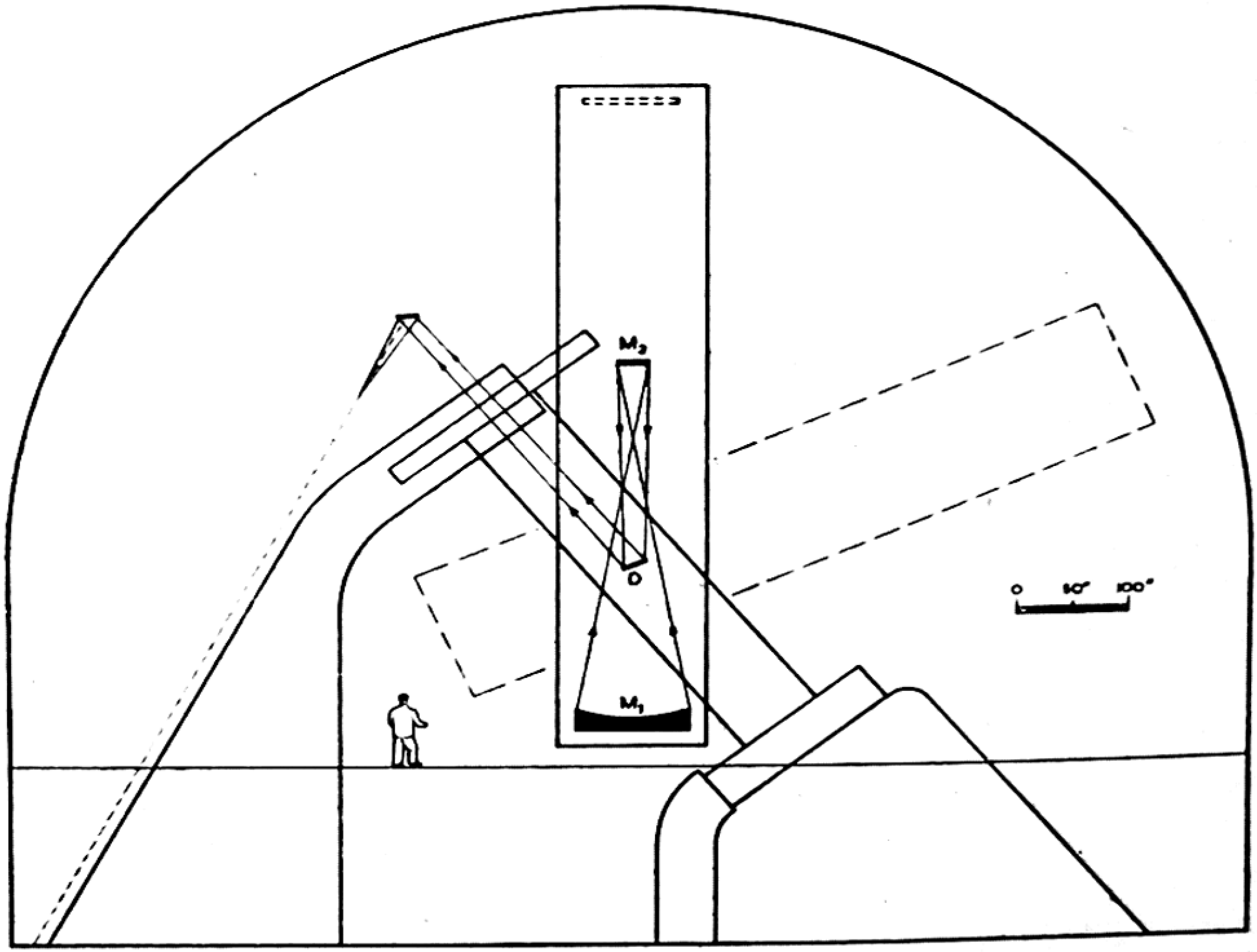


FIG. 15.7. Optical design of the Isaac Newton telescope. A fork mounting or a two-pier horseshoe mounting may be chosen.

mirror D, to allow coudé spectroscopy in a fixed, temperature-controlled chamber. One of the advantages of this arrangement is that the secondary M_2 need not be touched when changing over from Schmidt photography to spectroscopy and vice versa. This is important, because the centring of M_2 will be very critical, and an unusually careful design of the mounting of M_2 will be necessary to maintain its alignment to the needed accuracy.

The size of the corrector plate is not yet finally decided; if the telescope is to work with 14 inch × 14 inch photographic plates, then a working diameter of 85 inches in the corrector plate is what is needed to avoid vignetting on the one hand and waste of mirror-aperture on the other.

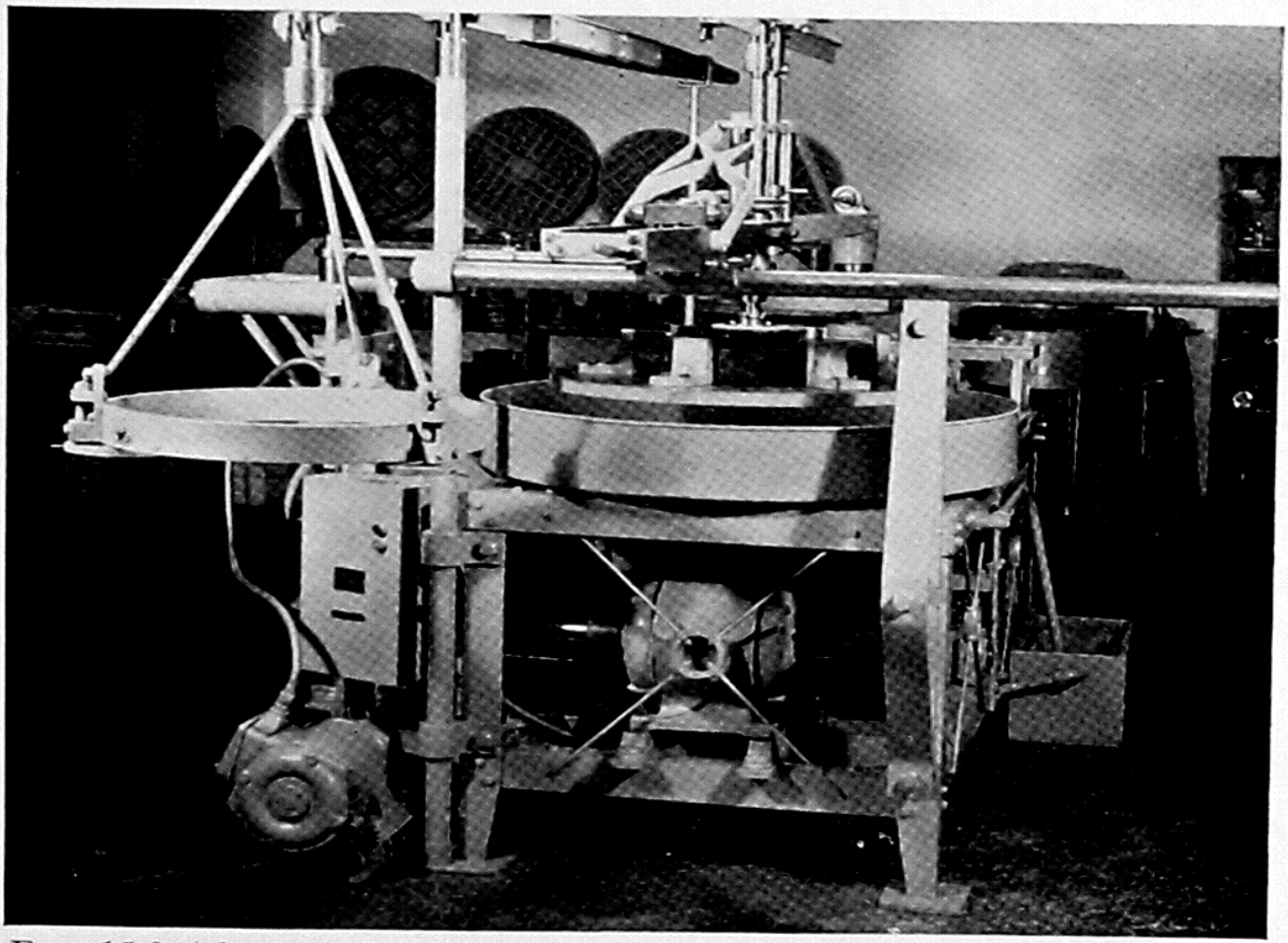
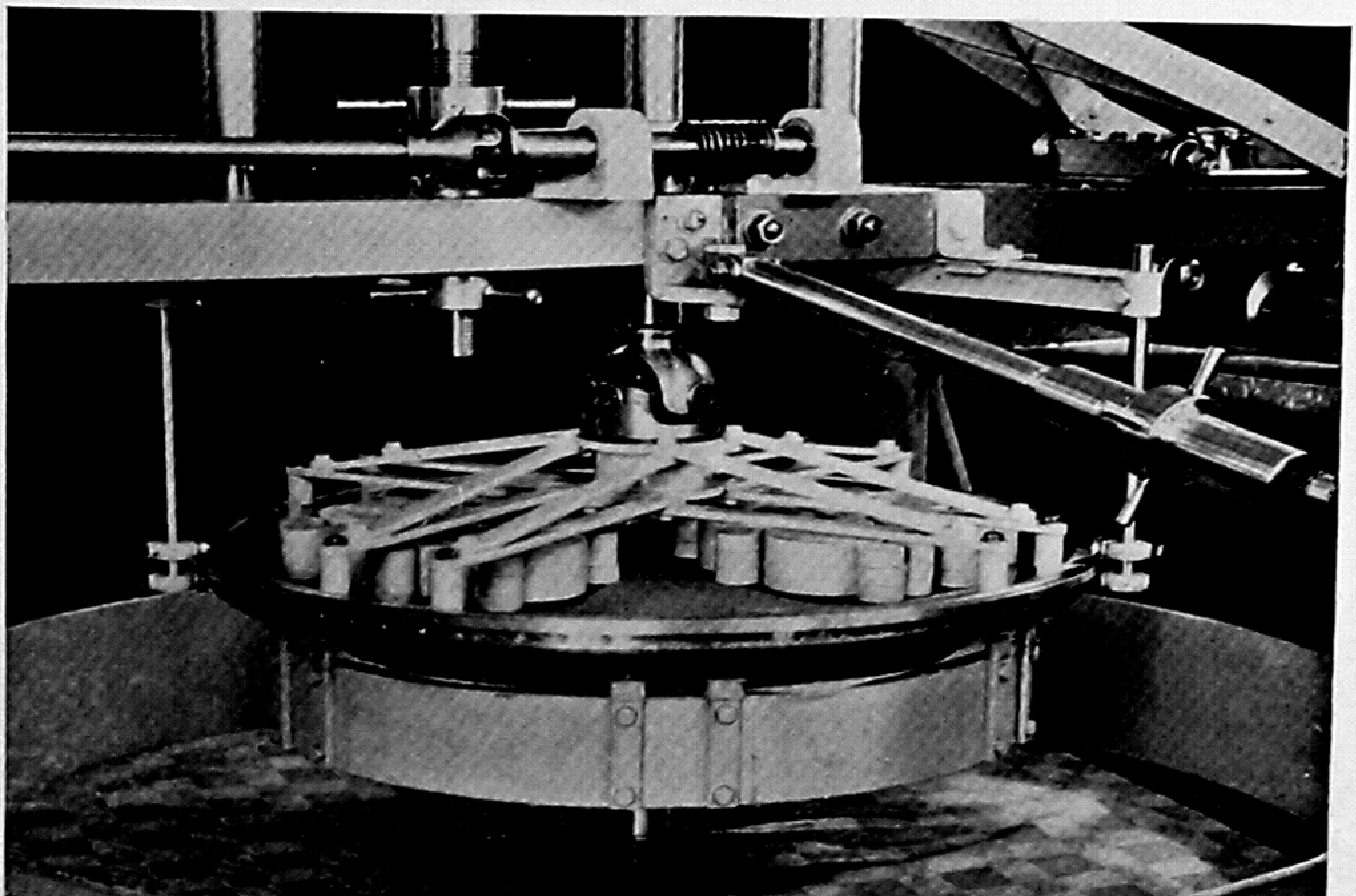


FIG. 15.3 (above). Grinding and polishing machine in the St. Andrew's Observatory Workshop. A 19-inch disc is shown in process of being rough-ground with a sub-diameter glass tool.

FIG. 15.4 (below). Asphering the corrector plate of the St. Andrew's 15/19-inch Pilot model. Petal-shaped areas of a flexible polishing lap are loaded with metal weights. The lap is given short traverse-strokes over the rotating plate. The universal joint is locked during this operation.



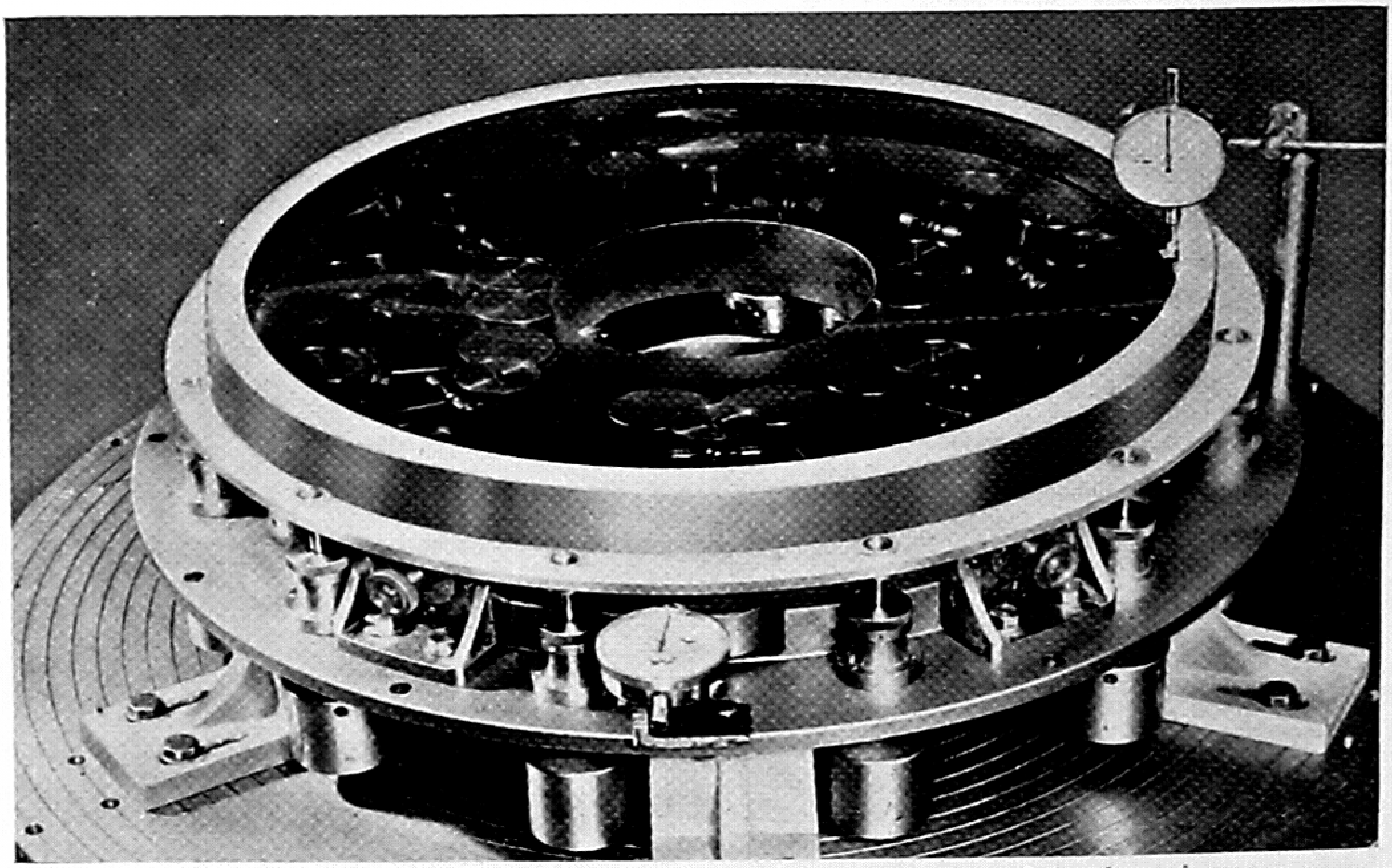


FIG. 15.5. Counterpoise support system of the 19-inch mirror.

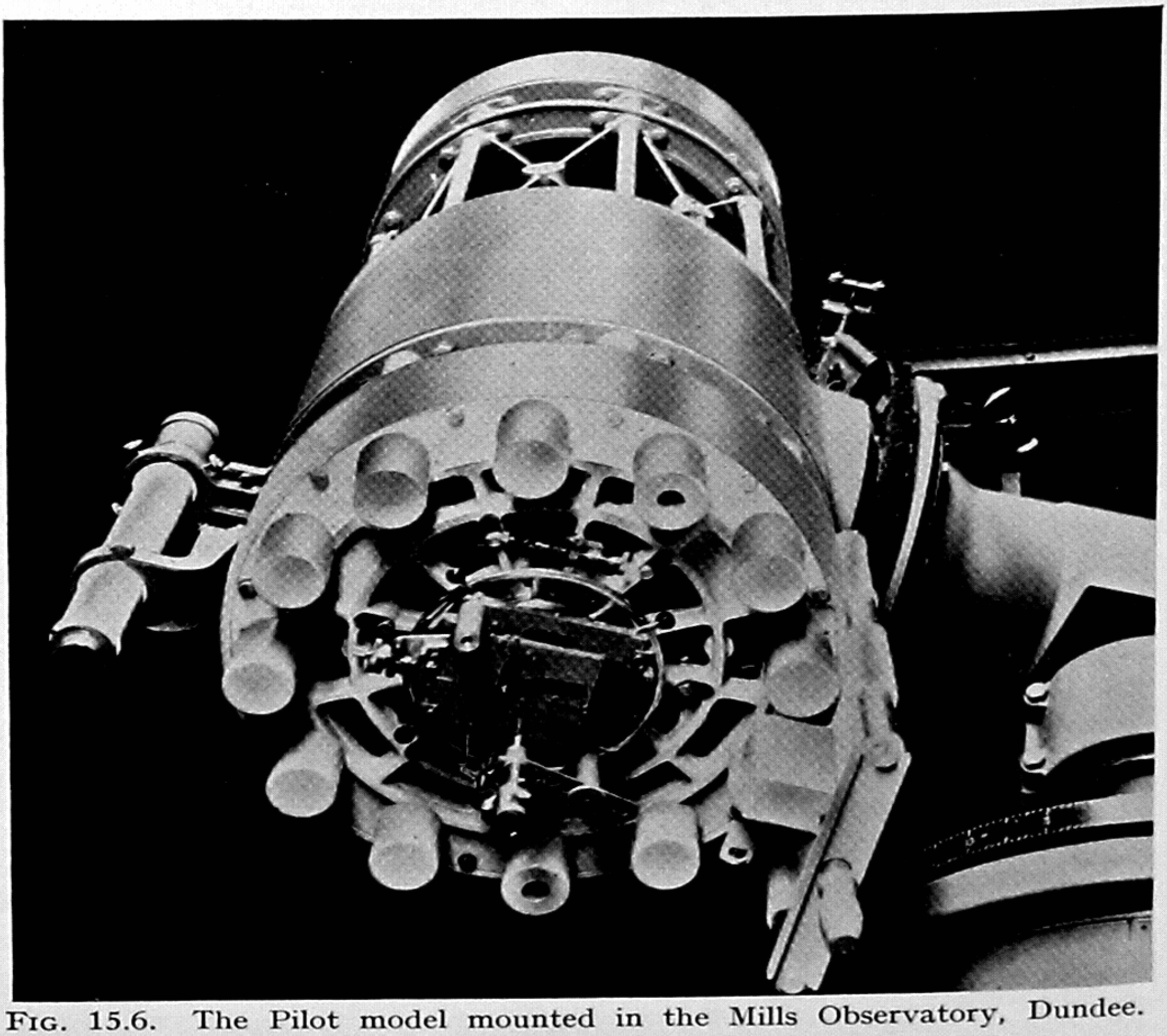


FIG. 15.6. The Pilot model mounted in the Mills Observatory, Dundee.

For low dispersion spectroscopy at prime focus it will be necessary to work with the corrector plate in position. This is a regrettable necessity, because the corrector plate cuts down the aperture of the telescope, and also cuts off the ultraviolet end of the spectrum. Nevertheless I believe that the present design, or something very close to it, represents the best that can be done with the means at our disposal. The construction of such a telescope must necessarily be a slow process, but it is gratifying to note that Messrs. Grubb Parsons have already started work on the 98-inch mirror disc, so that here, at least, no time is being lost.

Dual Purpose Telescopes

The problem of a modern observatory which has to decide whether to instal one large Newtonian telescope or one large Schmidt camera is not an easy one. Cambridge Observatory, partly because of the necessity of using existing domes to house its new equipment, has decided on a 17–24-inch Schmidt camera and a 36-inch Newtonian instead of on a single, larger telescope. Most of the less conservatively minded European observatories have gone for the Schmidt camera, whose great possibilities are still not fully explored. St. Andrews University and the ADH triumvirate have decided for Schmidt-Cassegrain cameras and the Vatican Observatory for a field-flattened Schmidt. Helwan in Egypt is building a simple Newtonian, as are Mount Stromlo in Australia and Lick in U.S.A.

Thus, except where special circumstances exist, observatories have felt that they had to make up their minds whether to go for a Schmidt or a Newtonian. The harshness of the choice is mitigated by the possibility of adding field-correctors to paraboloid reflectors, but the two-lens correctors originally proposed by Ross for the elimination of coma do not give anything like the performance of a Schmidt telescope, and later, more complex designs due to Baker and to Wynne have not so far found much favour with astronomers.

One or two observatories are considering having an interchangeable pair of mirrors—for example an f/3 sphere and an f/5 paraboloid—each in its own cell; the sphere is used together with a corrector plate, fixed to the top end of the tube, the paraboloid together with a diagonal flat or at prime focus. The weights can be so proportioned that when the telescope is converted from Newtonian to Schmidt or *vice versa*, no rebalancing is necessary. Nevertheless, I think that the difficulties of operating such a convertible system in practice would be rather serious. For in the first place, the mirrors and their cells are very heavy and one might fear a mishap with them every ten years or so. Secondly the mutual alignment of photographic plateholder and mirror is a tricky job which would need to be done afresh, to an accuracy measured in thousandths of an inch, every time the change-over was made. Thirdly, a change-over of spiders would be needed, as well as of mirrors, if unnecessary diffraction effects are to be avoided.

For these reasons, I think that in practice such a system would not be as flexible as it appears in theory. Fig. 15.8 shows an alternative design for a convertible telescope which seems to me to offer some advantages over those previously suggested. It consists of an f/4 paraboloid, mounted in a square tube of length equal to twice the focal length of the paraboloid. Immediately in front of the mirror is an aspheric plate carried in a mounting which can be hinged back against the side of the tube. This plate is of such a form that when placed in front of the paraboloid, it effectively converts it back into a sphere. At the front end of the tube is an ordinary Schmidt corrector plate, which can be hinged back against the opposite side of the tube from the first plate.

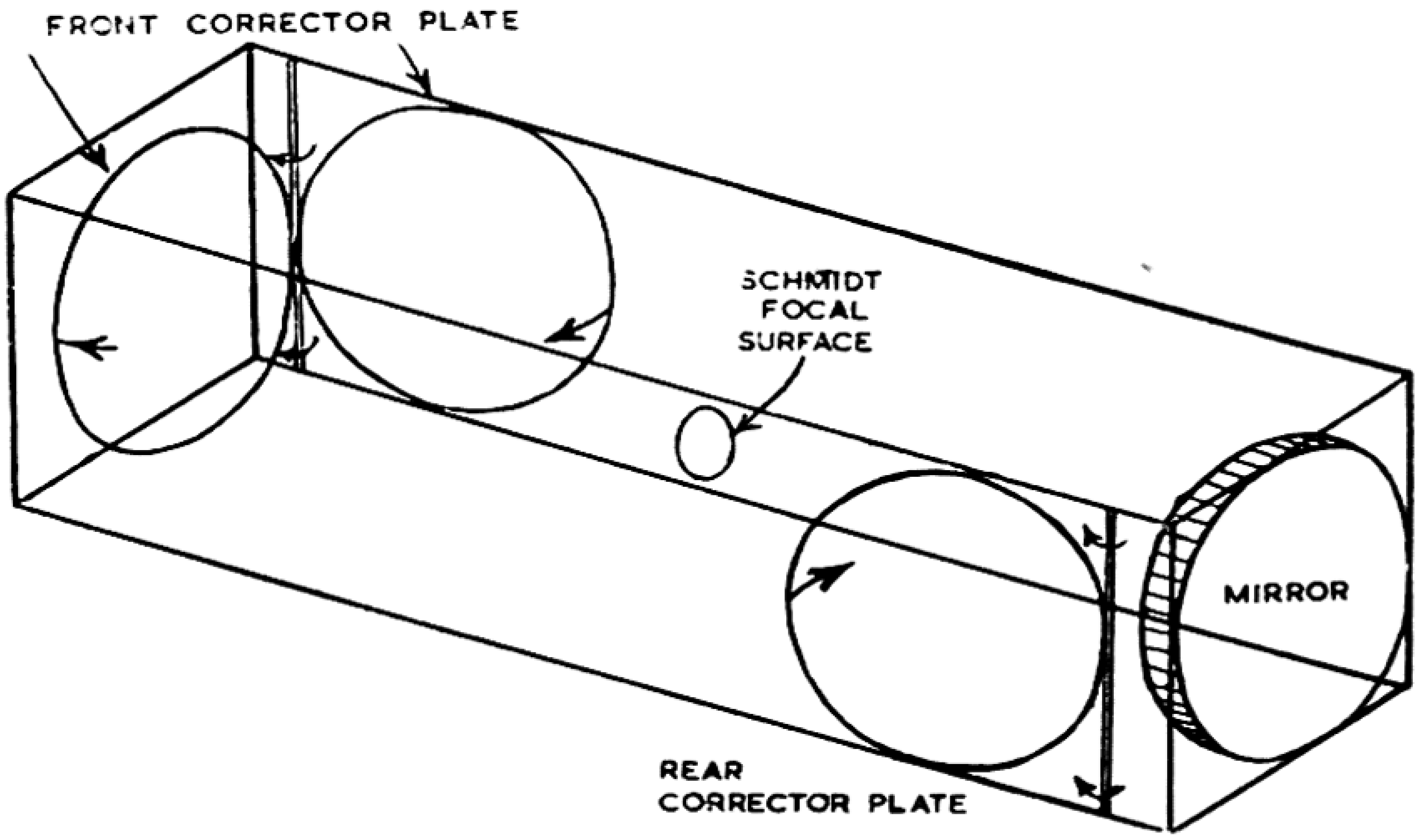


FIG. 15.8. "Convertible Schmidt" telescope. With the corrector plates folded back it is a Newtonian, with the plates in position its properties are closely similar to those of the ordinary Schmidt telescope.

With both plates hinged out of the light beam, the telescope is an ordinary Newtonian, which can be equipped with Cassegrain and coudé secondaries in the usual way. With both plates in position in the beam, it is substantially equivalent in its properties to a

Schmidt camera. Close to the axis, indeed, the images are even better than those of the Schmidt camera because of the nearly perfect colour-compensation between the two corrector plates, which are both made of the same kind of glass. At two degrees off axis, the colour properties are not so good as those of a Schmidt camera, but are harmless in practice, since for no ray does the colour-spread exceed twice that of an f/4 Schmidt camera. Mr. P. A. Wayman, who is at present working with me in Cambridge, is investigating the fifth order aberrations of this " convertible Schmidt " system in more detail.

By making the two corrector-plate assemblies of nearly equal mass, we can secure that the system is not thrown out of balance on its mounting when the change over is made. Then an astronomer may begin his night's work with a Schmidt camera exposure of, say, two hours duration and later, finding that the seeing has gone off but that the sky remains clear, may change over in a matter of twenty minutes to spectroscopic work in the ultra violet. In a climate like ours, where rapid atmospheric changes are the rule rather than the exception, an easily convertible telescope of this kind has much to recommend it.

SOMMAIRE

SUMMARY

La direction moderne dans le dessin des telescopes. Les télescopes d'ouverture et de champ large. Les considérations pratiques qui limitent le dessin et la construction. Les télescopes Schwarzschild à deux miroirs. Les télescopes Ritchey-Chrétien. L'appareil Schmidt et des systèmes qui s'y rapportent. Le télescope de St. Andrews. Le télescope Isaac Newton. Le problème du télescope à usage duel. Les correcteurs de champ pour les paraboloides. Le système " Schmidt convertissable."

Modern trends in telescope design. Large-field telescopes of large aperture; practical considerations limiting design and construction. Schwarzschild's two-mirror telescopes. The Ritchey-Chrétien telescopes. The Schmidt camera and related systems. The St. Andrews telescope. The Isaac Newton telescope. The problems of the dual purpose telescope; field correctors for paraboloids. The "convertible Schmidt" system.

DISCUSSION ON REFLECTING TELESCOPES

MR. J. W. PERRY: "In order to assist in reducing the variation of temperature (referred to by the Chairman) of round large reflector discs, would it not be advantageous to deposit a heavy coating of some highly conducting metal on all surfaces other than the aluminised optical surface? The proposed Schmidt system described by Dr. Linfoot suffers from some drawbacks by comparison with the reflectors of hitherto, which it would be very desirable to remove. The Schmidt corrector plate limits the range of transmission in the near ultraviolet owing to the non-availability of a suitable optical material transmitting sufficiently into the ultraviolet. The single plate Schmidt has chromatic defects which can be reasonably well corrected in a two-plate system having incidentally the advantage of requiring not such a great increase in length. Would not such a two-plate system be preferable? I think it desirable, as this is an international meeting, to point out that the method of Ronchi, referred to by Dr. Linfoot, and the methods of Lenouvel and Bates all depend upon 'wavefront shearing' and are in the limit identical in principle."

16. Recent Swiss Developments of Reflecting Telescopes

W. LOTMAR

(Kern & Co., Switzerland.)

IN 1936 Dr. H. Wild was concerned with the construction of a new high precision theodolite for first ordersurveying, to be manufactured by Kern & Co. The telescope was to have a magnification of 40 × in order to allow a full utilization of the measuring accuracy attained by means of a new special ball bearing system for the vertical axis. Furthermore it seemed desirable that this telescope should exhibit a high degree of optical correction, a reduced transit height, great luminosity and a relatively great focal length enabling the use of an eyepiece of not too high a power.

Telescopes for theodolites known hitherto, generally consisting of a three-part objective and a focusing lens, did not meet these demands, mainly because of their residual secondary spectrum which it was not possible to reduce. Studies for a new solution resulted in the system shown by Fig. 16.1 : A two-part objective L_1L_2 in combination with a backsilvered mirror lens L_3 forms an image B_1 on a small prism situated between these two elements. The rays are directed on to a second backsilvered mirror lens L_4 at right angles to the objective axis which forms a second enlarged image at B_2. By choice of appropriate glasses it was possible greatly to reduce the secondary spectrum. The degree of correction attained is shown in Fig. 16.2. For comparison, the correction of a conventional refracting telescope with a focusing lens is shown in Fig. 16.3. With a focal length of 430 mm., its transit height is 133 mm., whereas for the new telescope it is only 75 mm.

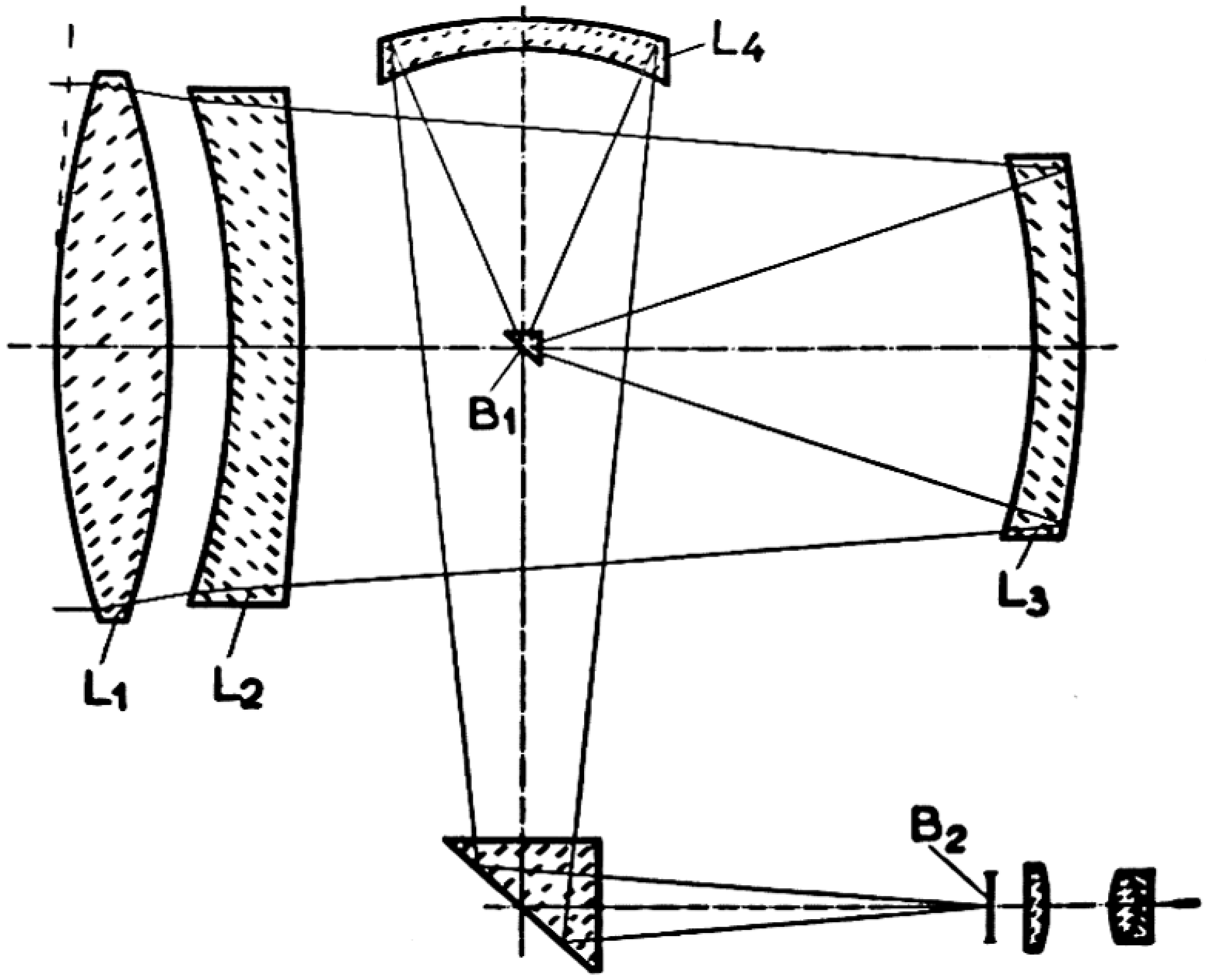


FIG. 16.1. Diagram of new telescope for theodolite. (A view of the instrument is given on Plate 8, facing p. 192.)

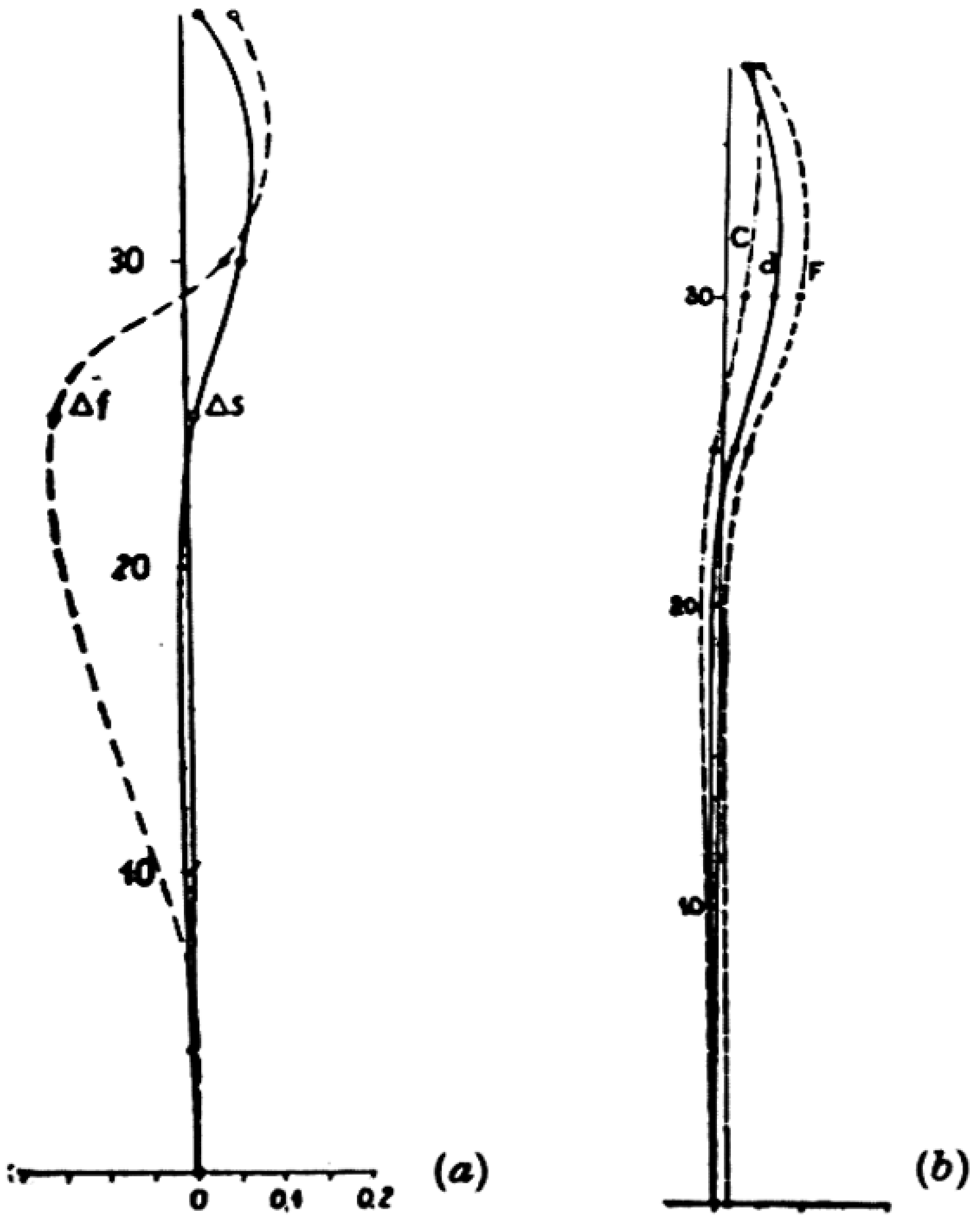


FIG. 16.2. Optical correction of the new telescope. Focal length 430 mm. (a) Intersection and focal length aberrations for *d*. (b) Intersection length aberrations for *C*, *d* and *F*.

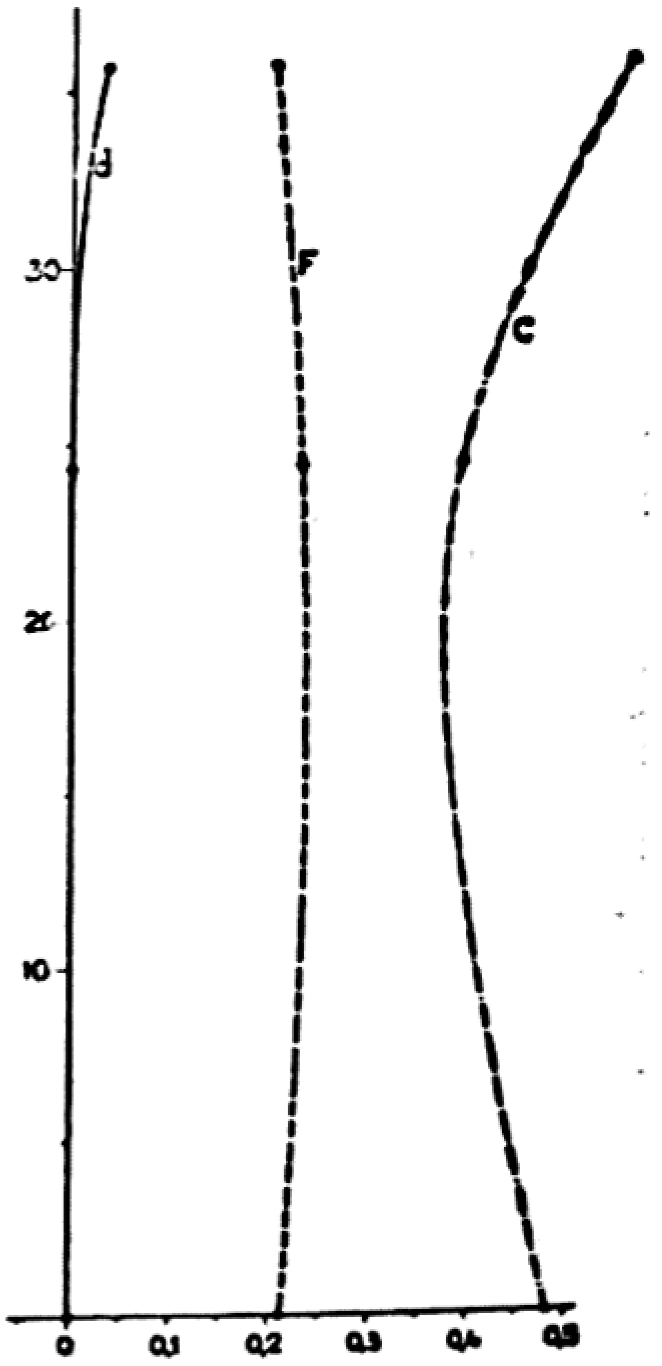


FIG. 16.3. Correction of conventional telescope shown for comparison.

Further characteristics of the latter are the erected image, an aperture ratio of f/5·7 and a light loss caused by the small prism of about 10%. This design with crossed axes prevents any stray light from reaching the eyepiece.

Ghost images formed by the front faces of the mirror lenses are rendered harmless by focusing them far away from the main image and may be practically eliminated by blooming.

A view of the new instrument is seen in Fig. 16.4, page 192.

The same optical system has been used for an astronomical universal theodolite with an aperture of 100 mm. and a magnification of 80 ×.

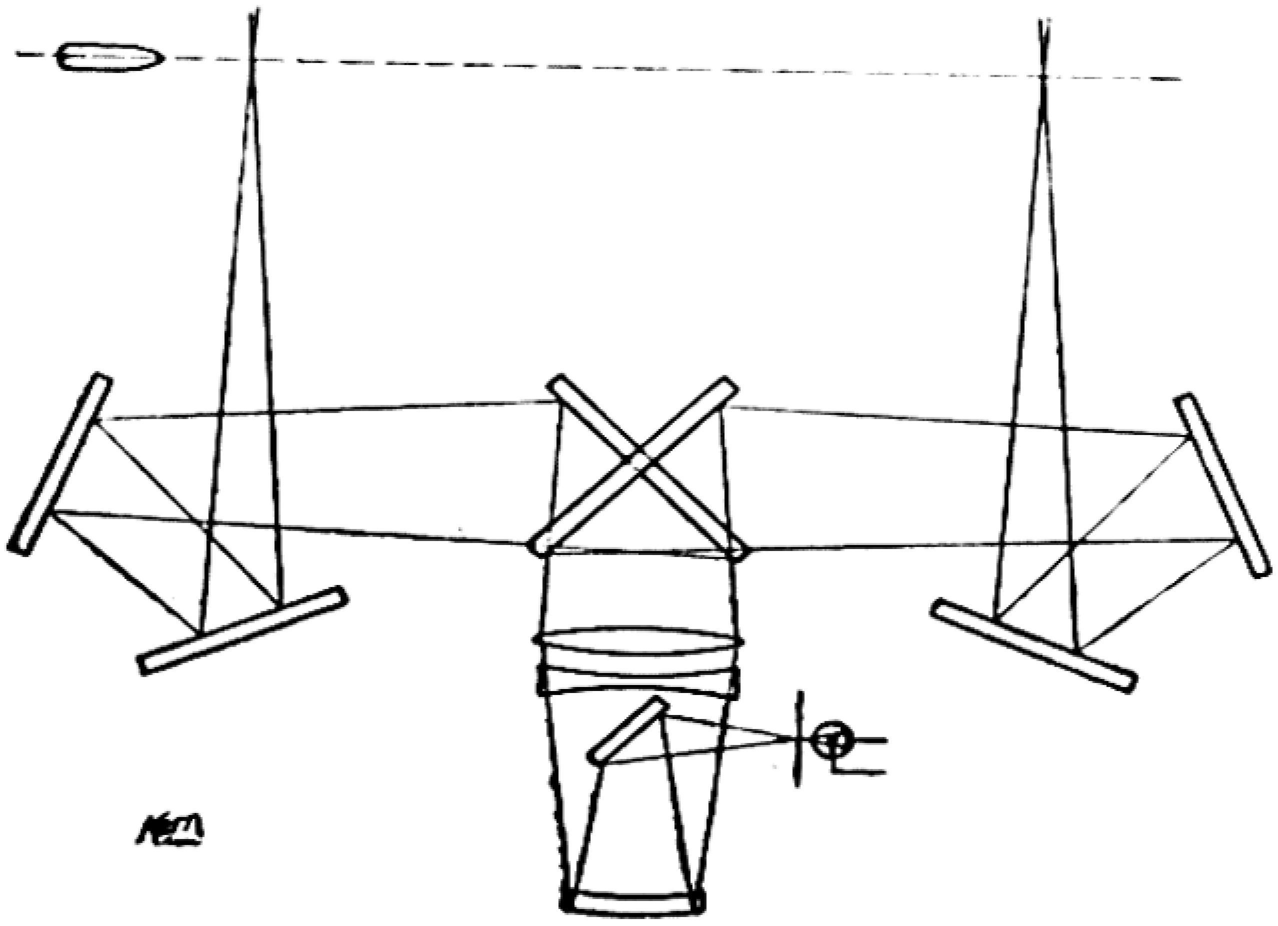


FIG. 16.6. Diagram of projectile velocity measuring apparatus for use with electronic timer.

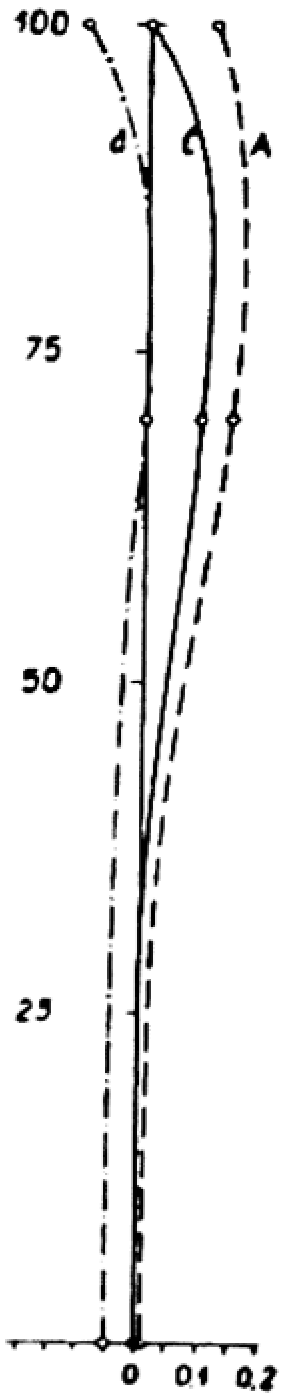


FIG. 16.7. Correction of objective shown in Fig. 16.6.

Furthermore the new system lends itself very naturally to the design of a binocular "scissors" type telescope. For this purpose the distance between the mirror lens L_4 and the eyepiece axis has only to be increased to the desired length. As there is no need for objective prisms, the entrance pupil may have a considerable diameter. The Swiss Army was provided with binocular telescopes 12 × 72 of this type showing a field of vision of 80 $^0/_{00}$. In this instrument the angle between the objective axis and that of the lens L_4 deviated somewhat from 90° so that steep sighting was facilitated (Fig. 16.5, page 193.)

In the telescopes described above the optical correction is accomplished only at the final image B_2, whereas the intermediate image B_1 must be deliberately left uncorrected in order to compensate for the errors of the mirror lens L_4. It is nevertheless also possible to correct the first part of the system ($L_1L_2L_3$) completely. Advantage was taken of this possibility in the design of a new instrument measuring the starting velocities V_0 of gun projectiles. This instrument has been developed by the Department of Technical Physics of the Federal Institute of Technology in collaboration with Kern & Co. The time lapse between the projectile's passing two virtual images of a slit formed by means of an objective and a mirror system Fig. 16.6 is recorded electronically. The objective used was of the catadioptric type shown in Fig. with a focal length of 550 mm. and an aperture ratio of f/2·8. Its correction is shown in Fig. 16.7. Objectives of this type with even much larger aperture ratios may also be corrected successfully.

The calculations of the systems described were made by Dr. H. Wild and Mr. H. Wild jr. (with Kern & Co.).

SOMMAIRE SUMMARY

Dans le cours de la construction d'une nouvelle théodolite de haute précision en 1936 par Dr. H. Wild, on a éprouvé la necessité de fournir cet instrument d'un télescope qui montrait une condition améliorée de correction optique, comparée à celle jusqu'a connue. Les télescopes qui servent de modèle étaient alors fournis d'habitude d'une lentille focale qui, pendant qu'elle avait égard a une correction sphérique satisfaisante, augmentait le spectre sécondaire et par consequence mettait obstacle à un montage précis.

Les conditions requises pour le nouveau télescope étaient :

1. Une bonne correction optique.
2. Courte hauteur de transit (stabilité).
3. Grande luminosité.

On a trouvé la solution dans une combinaison de lentilles et de miroirs aux surfaces exclusivement spheriques. Ou a décidé qu'il fallait que les miroirs soient du type Mangin (argentés derrière) afin de guaranti une stabilité maxime de la couche de métal. Le système se compose d'un objectif (en deux parties) à face positive,

et d'une lentille à miroir du premier type Mangin sur l'axe objectif ce qui produit une première image réelle entre ces deux éléments. Cette image est jetée sur un petit prisme de 90° qui dirige les rayons sur une seconde lentille a miroir Mangin à angle droit à l'axe objectif, qui forme une deuxième image réelle magnifiée. Ceci est divié par un autre prisme de 90° dans l'oculaire dont l'axe est parallèle à l'axe objectif mais déplacé à son égard ; l'image qui en résulte est droit. Par l'emploi de lunettes d'une dispersion presque égale, il est possible de supprimer complètement le spectre sécondaire, tandis que l'erreur sphèrique qui reste est moins que, 0·2% de la longeur focale. La surface couverte par le prisme derrière l'objet ne répresente que, 0·5% de la pupille d'entrée. Ces chiffres se rapportent à un objectif de distance focale de 430 mm. et d'ouverture 75 mm. (f : 5·7).

L'hauteur de transit de ce télescope n'est que 75 mm. Le même système a été employé pour un télescope militaire binoculaire 12 × 72.

In the course of the construction of a new high precision theodolite in 1936 by Dr. H. Wild the necessity was felt of providing this instrument with a telescope which would show an improved degree of optical correction as compared with that known hitherto. Standard telescopes were then commonly fitted with a focusing lens which, while allowing for a satisfactory spherical correction, increased the secondary spectrum and therefore interfered with exact setting.

The requirements for the new telescope were therefore :—

(1) Good optical correction,
(2) Short transit height (stability),
(3) Great luminosity.

The solution was found in a combination of lenses and mirrors with exclusively spherical surfaces. It was decided that the mirrors had to be of the Mangin type (backsilvered) in order to ensure maximum stability of the metal coating. The system consists of a two-part positive front objective and a first Mangin type mirror lens on the objective axis, forming a first real image between these two elements. This image is thrown on a small 90° prism which directs the rays on to a second Mangin mirror lens at right angles to the objective axis, which forms a second real magnified image. This is deflected by another 90° prism into the eyepiece, the axis of which is parallel to the objective axis but displaced with respect to it. The resulting image is erect. By using glasses of nearly equal dispersion it is possible to suppress the secondary spectrum of the objective part completely, while the residual spherical error is less than 0.2 per cent. of the focal length. The surface occupied by the prism behind the objective is only 0.5 per cent. of the entrance pupil. These figures correspond to an objective of 430 mm. focal length and 75 mm. aperture (f : 5,7). The transit height of this telescope is only 75 mm. The same system has been employed for a military binocular telescope 12 × 72.

MISCELLANEOUS

17. Velocity of Light and Measurement of Distances

ERIK BERGSTRAND
(The Geographical Survey, Sweden)

AT the Geographical Survey of Sweden there has been tested an apparatus intended for measurements of distance by high frequency light signalling. It is based on the principle used by Fizeau for terrestrial determinations of the velocity of light modified by making use of a Kerr cell and a photo-cell. As a suggestion the apparatus is called " geodimeter." It is built by A.G.A. Ltd. and is in principle fairly like the first model, which Professor Siegbahn kindly allowed me to build at the " Nobelinstitutet for Fysik."

The geodimeter is conversely suitable for measuring the velocity of light. The information necessary is a knowledge of the distance used and of the frequency of the alternation of the light intensity. The principle will be made clear by Fig. 17.1.

L is a source of light having a spherical mirror to project the light as a beam. The source is controlled by high frequency supply from the crystal-controlled oscillator *Kr* and thus the intensity of the light emitted varies with the frequency of the oscillator. *S* is a plane mirror, which reflects back the light to the phototube *F*. *F* gets its operating voltage from *Kr*. Accordingly the sensitivity of the tube varies with the same frequency as the emitted light. As the flashes of light spend a certain time to cover the way to *S* and back again, the moments of high sensitivity of the tube will be more or less timed to the incoming flashes, depending on the distance *D*. Thereby the currents taken from the tube will vary with the distance as seen in (*b*).

At $D=0$ we get a maximum current, assuming that the moments of high intensity of light and high sensitivity of the tube coincide. Sharply defined positions of the mirror cannot be taken from this curve. However, suppose we had an apparatus equal to that in (*a*) but for the phototube having the moments of high sensitivity simultaneously with minimum of intensity from the lamp. Then we would get a current as in (*c*).

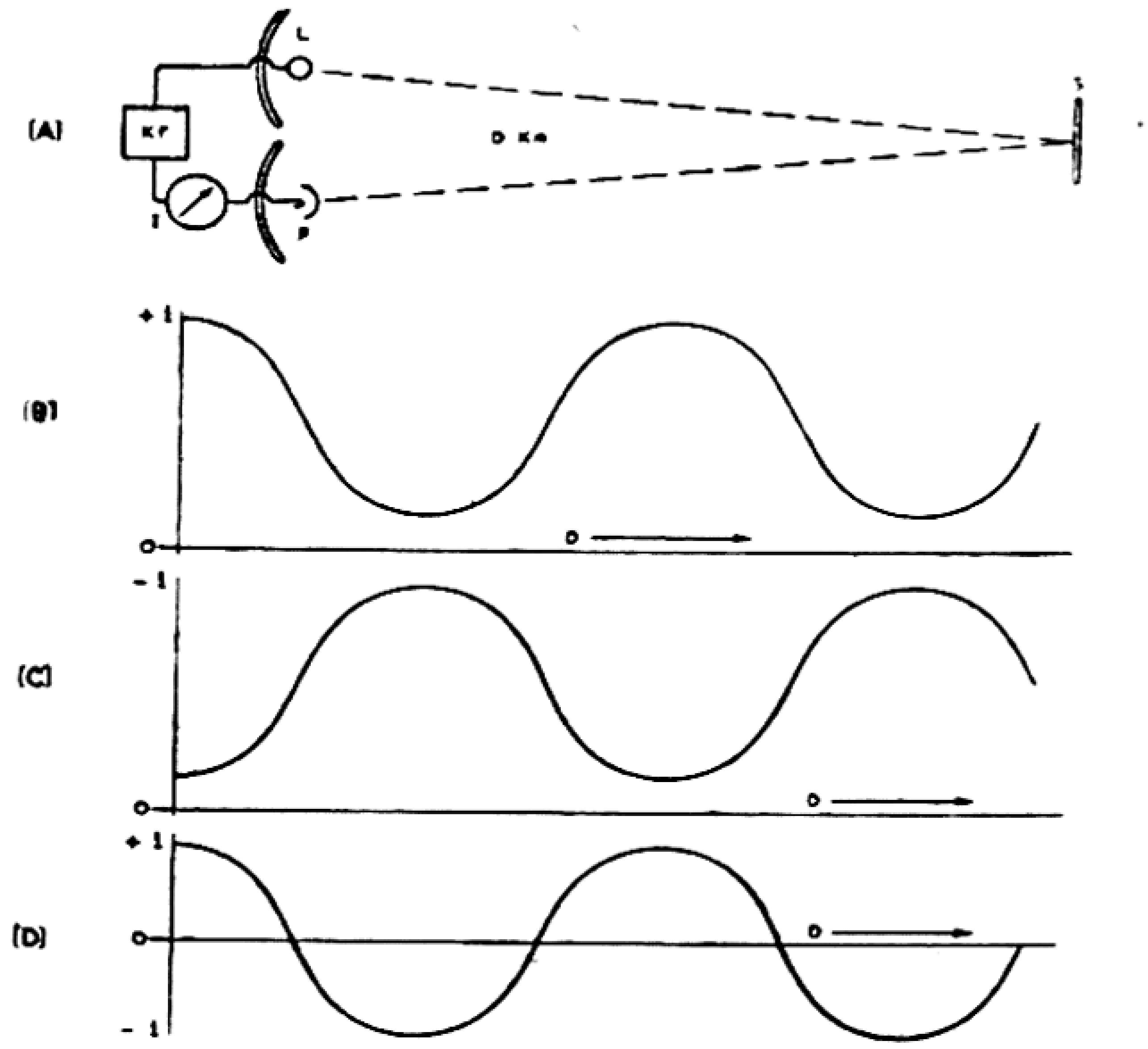


Fig. 17.1. Diagram to illustrate the principle of measurement by the geodimeter.

Sending the currents as in (*b*) and (*c*) in opposite directions through a measuring instrument we read off the difference as in (*d*). Now we get sharply marked positions of the mirror where the current is zero and the variation of signal strength is large. It is difficult to get the two pieces of apparatus precisely equal. For that reason only one apparatus is used but it is made to work alternately as each of the two. The alternation is effected by a low-frequency voltage in a way which will be made clear later. During the positive and the negative half-cycles the current is supplied in reversed directions to a slow-acting instrument, which thus shows the current as in (*d*).

In Fig. 17.2 we see a little more detailed scheme. *L* is the source of light, a 30-watt incandescent lamp, S_1 and S_2 are 45 cm. spherical mirrors, S_3 a plane mirror, 1, 2, 3, 4, 5, LS_1 and LS_2 are lenses and mirrors, F is a vacuum phototube (R.C.A. IP21) and I a microammeter indicating current from F. Ke is a Kerr cell, which produces the light variation. N_1 and N_2 are crossed Nicols, belonging to Ke.

Outside the prism N_2 the intensity of the light depends on the voltage in accordance with the equation :

$$J = J_0 \sin^2 kV^2 \tag{1}$$

where J=intensity, J_0 and k=constants, V=difference of potential between the plates.

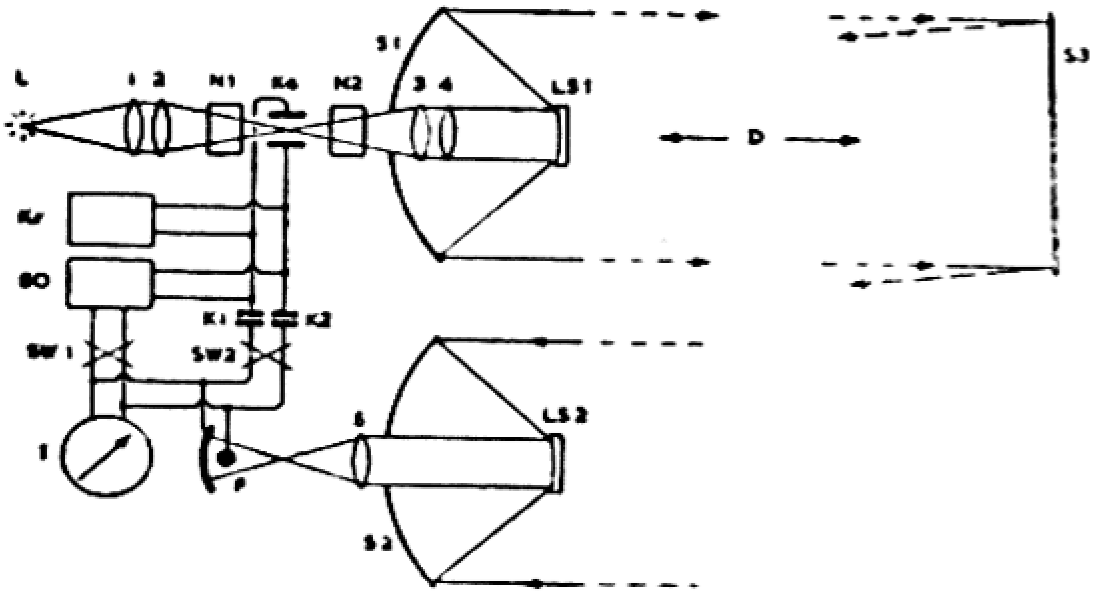


FIG. 17.2. Detailed diagram of apparatus.

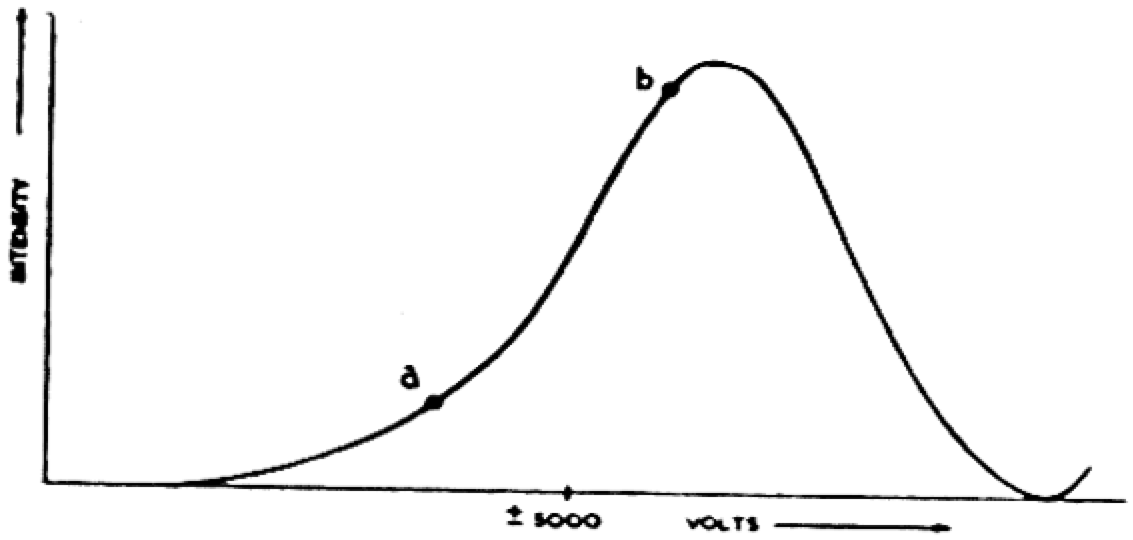


FIG. 17.3 Characteristic of Kerr Cell.

In practice, dependent on the purity of the nitrobenzene in the cell, k is somewhat dependent on V and dV/dt. Therefore the real intensity of the light as a function of the voltage is not fully identical with the curve shown in Fig. 17.3 :

Between a and b the curve is fairly straight. If the cell has a constant bias voltage between these values and an alternating tension of limited amplitude is superimposed, the variations of the intensity of light assume the same shape as the alternating tension plus a constant quantity of light, the latter depending on the bias voltage. The plates in Ke are fed by the crystal oscillator Kr with high frequency voltage of 8 Mc/s and amplitude 2000 volts and also from the set 50 with 50-cycle voltage having the amplitude 5000 volts.

The most favourable condition is attained when the 50-cycle oscillation has a square wave-form. The result is a completely constant bias voltage half-way between *a* and *b* and this voltage changes sign 100 times a second. A tolerable approximation to square shape is attained by cutting off the tops of a sine voltage. The high frequency however, has a pure sinusoidal shape. At the plates of the Kerr cell this voltage is assumed to have the form :

$$V = a\sin\omega t, \tag{2}$$

where a=amplitude, $\omega = 2\pi n$, where n=frequency, t=time.

It takes a time t_1 to transform V into light variations just outside the prism N_2. Considering *a–b* in Fig. 17.3 to be a straight line, we can express the light intensity by

$$J_{50+} = C_1 + C_2\sin\omega(t - t_1) \tag{3a}$$

$$J_{50-} = C_1 + C_2\sin[\omega(t - t_1) + \pi] \tag{3b}$$

50^+ and 50^- indicate that the light is emitted during the positive or negative half-cycles of the 50-cycle alternation. C_1 is the constant intensity and C_2 the amplitude of the variation. The angle π in (3*b*) arises from the change in sign of the bias voltage.

When it has passed the distance D to the plane mirror S_3 and back again the light, or part of it, is absorbed by the photo-tube. During the positive *high frequency* half-cycles we get current from the anode. Assuming early saturation, we get the photo-current :

$$i_{50+} = \frac{n}{2}\int_{t_3}^{t_3+1/2n} [A + B\sin\omega(t - t_1 - t_2 - 2D/c)].dt \tag{4a}$$

$$i_{50-} = \frac{n}{2}\int_{t_3}^{t_3+1/2n} [A + B\sin(\omega(t_1 - t_1 - t_2 - 2D/c) + \pi)].dt \tag{4b}$$

A and B correspond to C_1 and C_2 of Eq. (3). In the time $2D/c$ (c=velocity of light), $2D$ is the whole distance from the prism N_2 (or, more exactly, from the point where t_1 in Eq. (3) was reckoned) to the mirror S^3 and exactly the same distance back again. The cathode of **F** is assumed to be here. t_2 is practically the transit time of the photoelectrons ($2{\cdot}4 \times 10^{-8}$s.) from cathode to anode. t_2 may be considered to include a further short time, due to the cathode not being placed at the end of the distance $2D$. The summation in Eq. 4 is done for one high frequency half-cycle, which begins at t_3 and ends at $t_3 + 1/2n$, t_3 being the transference time of the voltage from the Kerr plates to the photo-anode and n the frequency. The charge per second, or the current, is obtained after multiplying by $n/2$ the number of half-cycles in one second of 50^+ and 50^- respectively.

The two currents i_{50+} and i_{50-} have opposing influences on the instrument I, which thus makes a deflection proportional to the difference of the currents. From Eq. (4) we obtain:

$$i=i_{50+}-i_{50-}=\frac{B}{\pi}\cdot\cos\omega(t_3-t_1-t_2-2D/c) \tag{5}$$

The current will be zero for values of D, which fulfil the condition:

$$\omega\,(t_3-t_1-t_2-2D/c)=\frac{\pi}{2}-N\cdot\pi \tag{6}$$

where N denotes a whole number. With $\omega=2\pi n$ and $c=\lambda\cdot n$, we get:

$$D=\frac{n}{2}(t_3-t_1-t_2)\cdot\lambda+\frac{2N-1}{8}\cdot\lambda \tag{7}$$

or

$$D=K+\frac{2N-1}{8}\cdot\lambda \tag{8}$$

where K is a constant, n, t_1, t_2, t_3 being constants.

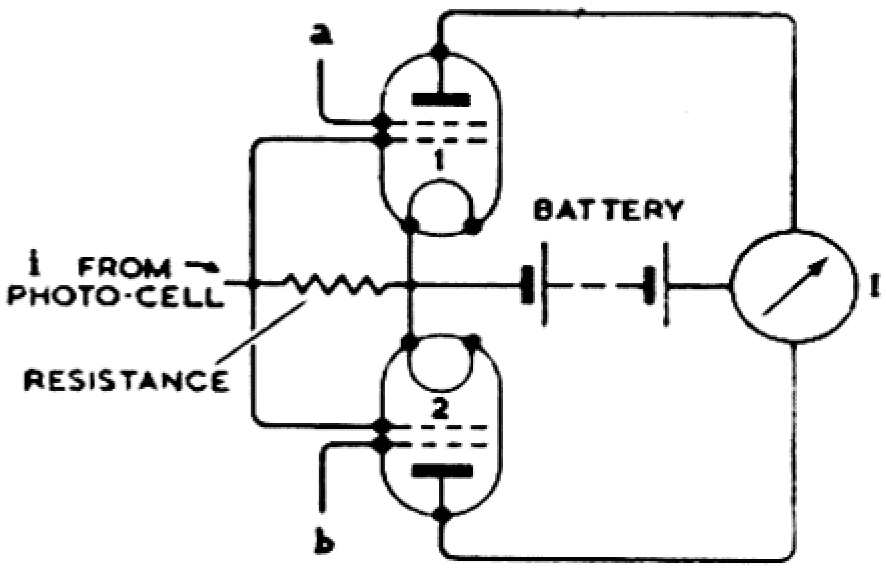


FIG. 17.4. Circuit for separating low frequency impulses.

In a Fourier expansion of the intensity R of the received light, we get a series of terms $A_n\cdot\sin n\,\omega t$ or $A_n\cdot\sin n\,(\omega t+\pi)$, the former for the positive cycle and the latter for the negative. The sensitivity S of the photo-cell contains an analogous series of terms $B\cdot\sin n\,\omega\,(t-\mathbf{q})$. $\mathbf{q}$ is due to the difference in phase as above:

$\mathbf{q}=t_1+t_2-t_3+2D/c$. The photo-current is represented by a series of terms $\pm H\cdot\cos n\omega\mathbf{q}$, ωt being cancelled out. The sign depends on the sign of the low frequency modulation,

$$i=i_{50+}-i_{50-}=M\cdot\cos n\omega\mathbf{q}=0$$

as in Eq. (5) and (6), and the same Eq. (8) results as before.

The separation of the low frequency impulses is shown in Fig. 17.4. The common control grids of the valves 1 and 2 receive the pulses 50^+ and 50^- from the photoanode. The suppressor-grids *a* and *b* however are supplied with an appropriate fraction of the 50-cycle voltage in such a manner that *a* has normal working potential simultaneously with *b* having maximum of negative potential. Thus valve 2 is blocked. During the next 50-cycle half-cycle valve 2 amplifies normally and valve 1 is blocked.

D in the Eq. (8) is the distance to the plane mirror. Taking the difference between two such distances, *K* will be eliminated and we get :

$$D_N = \frac{N}{4} \cdot \lambda \tag{9}$$

and D_N being known we get λ. *N* is easy to determine from approximate values. The frequency corresponding to λ being *n* and known, we get the velocity of light in air from :

$$c_a = n \cdot \lambda \tag{10}$$

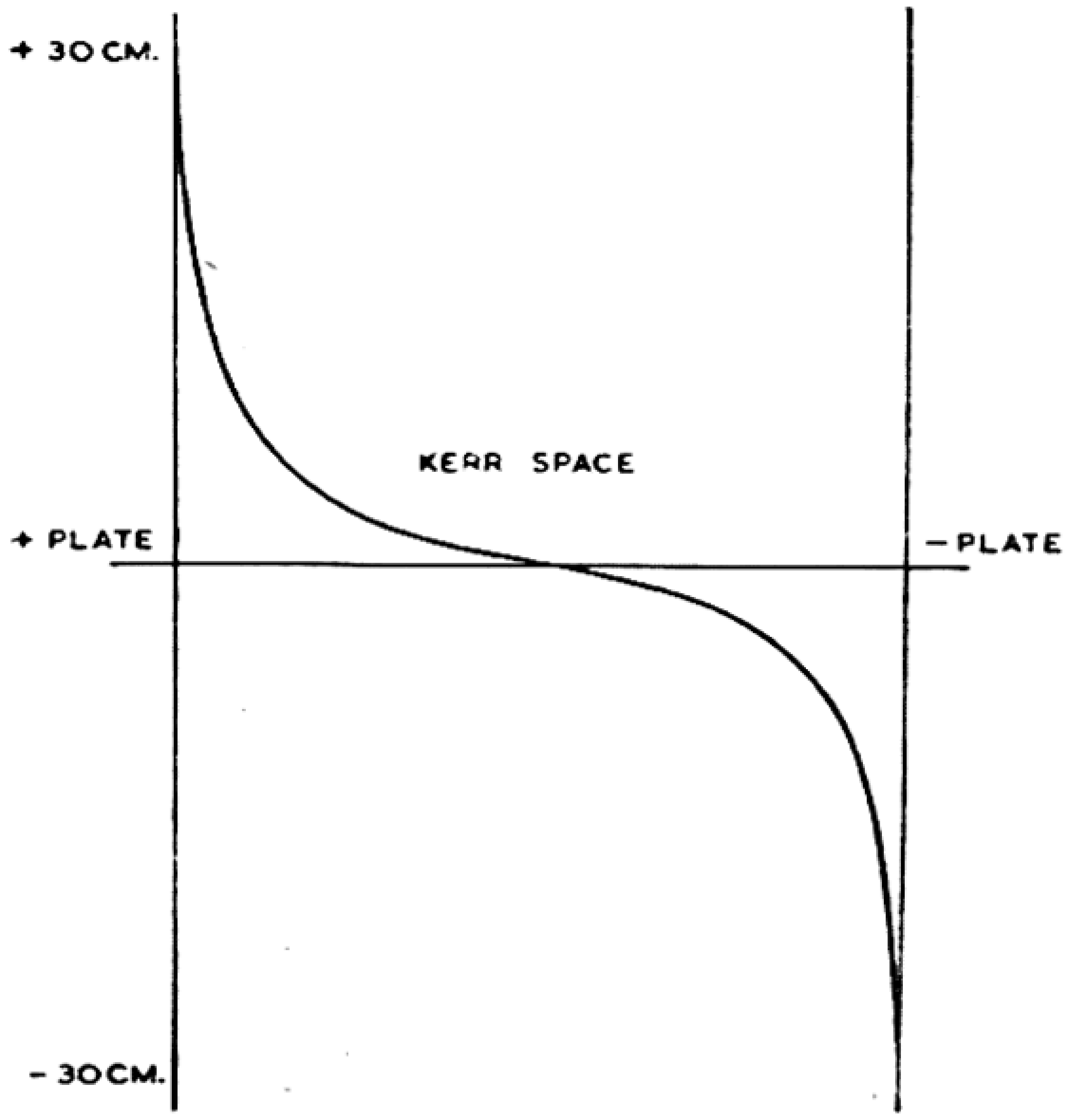


FIG. 17.5. Variation of phase with distance between plates in the Kerr cell.

In Eq. (9) D_N may be the distance between the nearest and the farthest zero-point as determined by the micro-ammeter indicating $i=0$ and may consist of a geodetic base-line. In the actual case D_N is the base-line at Enköping. $D_N = 6906\ m$, $N = 768$, $\lambda = 36\ m$, $n = 8{\cdot}332230$ Mc/s.

In practice the distant mirror is placed close to a zero-point (as read off on the micro-ammeter). The high frequency is changed

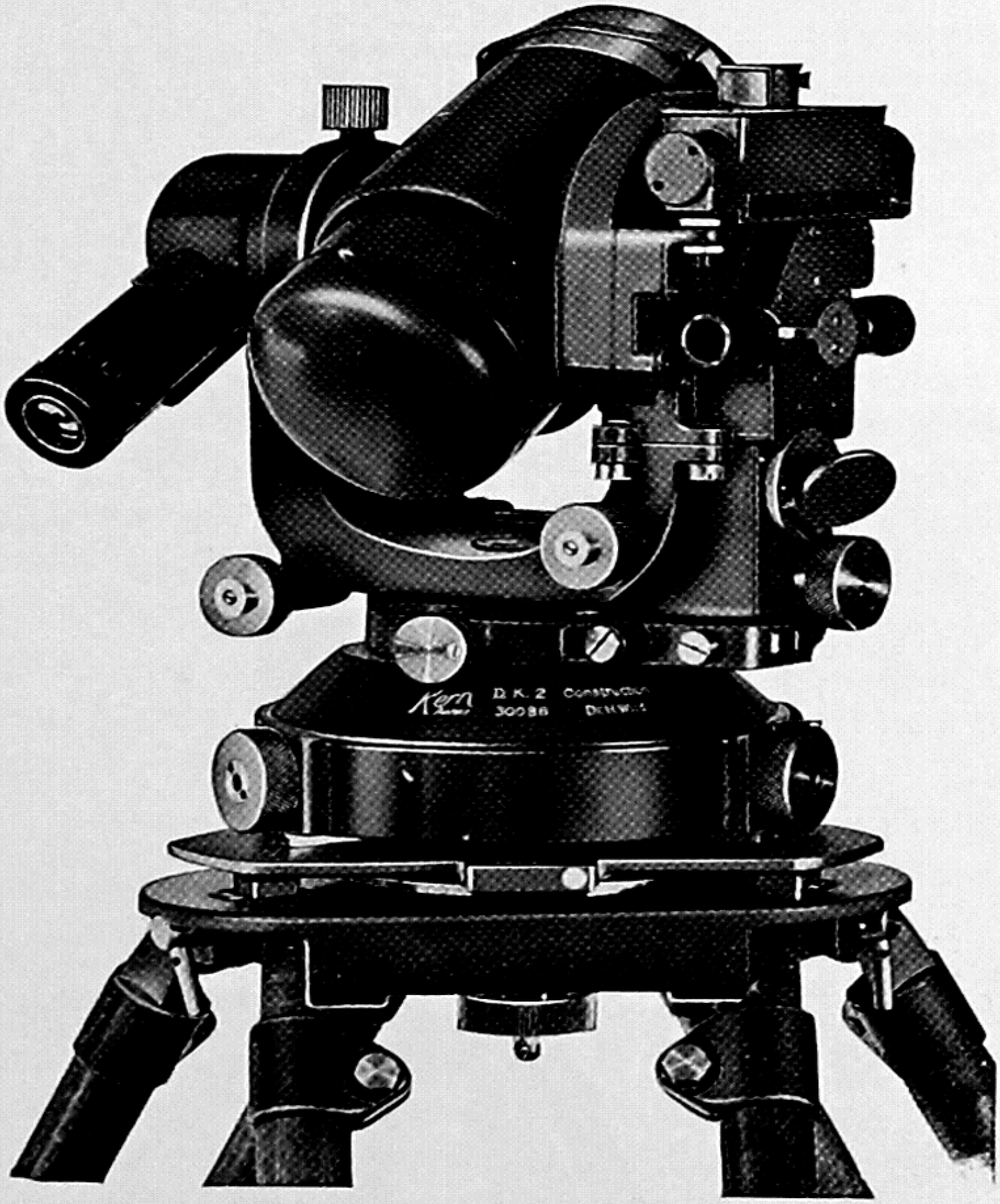


FIG. 16.4. Theodolite with new reflecting telescope (described on p. 181). (*By courtesy of Messrs. Kern and Co.*)

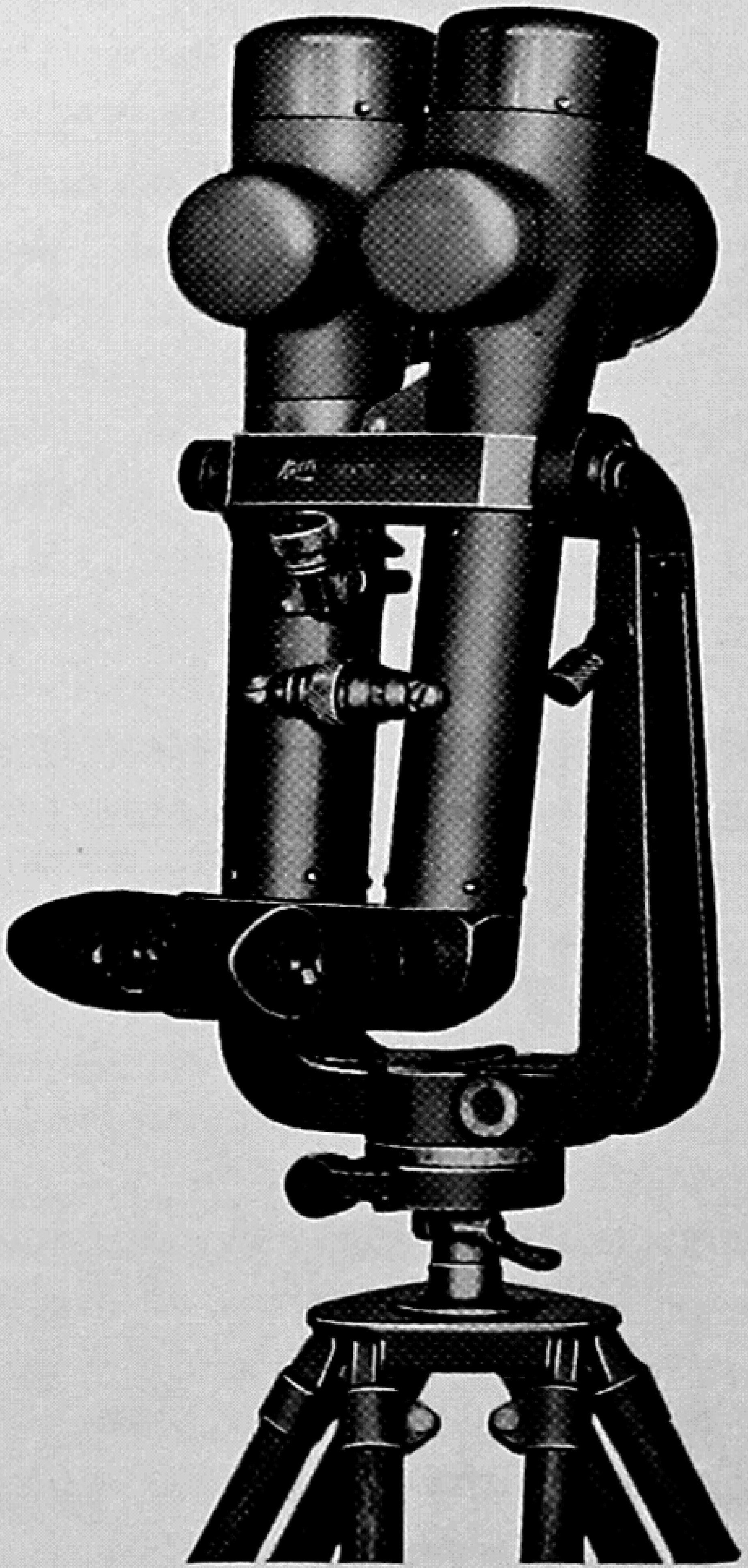


FIG. 16.5. Binocular telescope for the Swiss Army (described on p. 183).
(By courtesy of Messrs. Kern and Co.)

by a small ($<0{\cdot}1^0/_{00}$) definable amount until zero deflection is reached.

This single reading is impaired by a systematic unknown error, depending on the location of the mirror S_3 in the image of the light source. Different parts of the image have different phases, dependent on the part from which the light is emanating in the space between the Kerr plates. In Fig. 17.5 is shown the manner in which the change in distance corresponding to the variation of phase varies from the positive to the negative Kerr plate.

The curve is obtained at an appropriate distance D by progressively placing a very small mirror in different parts of the image of light.

The error will not be eliminated by the change of polarity, because of the simultaneously changing of phase of the valves 1 and 2 Fig. 17.4. However, we get two distances D if the connections to the Kerr plates are reversed, and by taking the mean we get a correct value because of the inverse symmetry of the curve in Fig. 17.5. In this way the error will be eliminated. Instead, however, of reversing at the high tension poles of the Kerr cell, two low tension reversing commutators *SwI* and *SwII* Fig. 17.2 are inserted, one in the high frequency feeding circuit to the photo-cell and the second in the 50-cycle circuit to the grids *a* and *b* (Fig. 4). Thereby the distance D is determined from the mean of four determinations corresponding to the four possible combined positions of the switches *SwI* and *SwII*.

To obtain the difference between two D:s according to Eq. (9) we also have to place the plane mirror at a comparatively small distance. In this case the adjustment cannot be effected by changing the frequency, as the necessary change would be too large. Instead there is a movable mirror at $D=90$ *m*. The mirror is made convex, so that the image to the geodimeter is equivalent to that from the distant mirror.

If K in Eq. (8) were really constant, K could be determined once for all. K, however, varies somewhat with t_1, t_2 and t_3. The variation hitherto has usually been less than two cms. Nevertheless it must be determined at each individual measurement. It is difficult to make a rapid change from $D=90$ to $D=7000$ *m*. Because of that the distance $D=90$ is used to calibrate a small loop of light, continuously variable and including the first zero-point where $N=1$ and $D=1$ *m* or so. In Fig. 17.6 we see the arrangement of the variable loop. The small plane mirrors 1, 2, 5 and a convex mirror 4 are fixed. The right angled mirror 3 is movable on a bar furnished with the 0–70 cm. scale. 1 and 5 can be moved aside, when the ordinary measurements are made. 4 being convex an appropriate quantity of light reaches the photo-cathode.

Unlike the light coming from the distant mirror, that passing through the loop emanates from all parts of the light source. The two paths of light are fully comparable only if the inverse symmetry of the curve in Fig. 17.5 is absolute. Not relying fully on this, we graduate the loop by measurements at $D=90$ *m*, and we can do that because a change of K will have the same effect in the loop as in the 90 *m* path. In all these measurements the value of D is a mean of four determinations as mentioned above. Such a mean did not show any marked change if the light used came from the middle or the one or the other half of the space between the Kerr plates. Thus the situation of the image of L between the Kerr plates need not be exact, and the inverse symmetry of the curve in Fig. 17.5 seems to be very good.

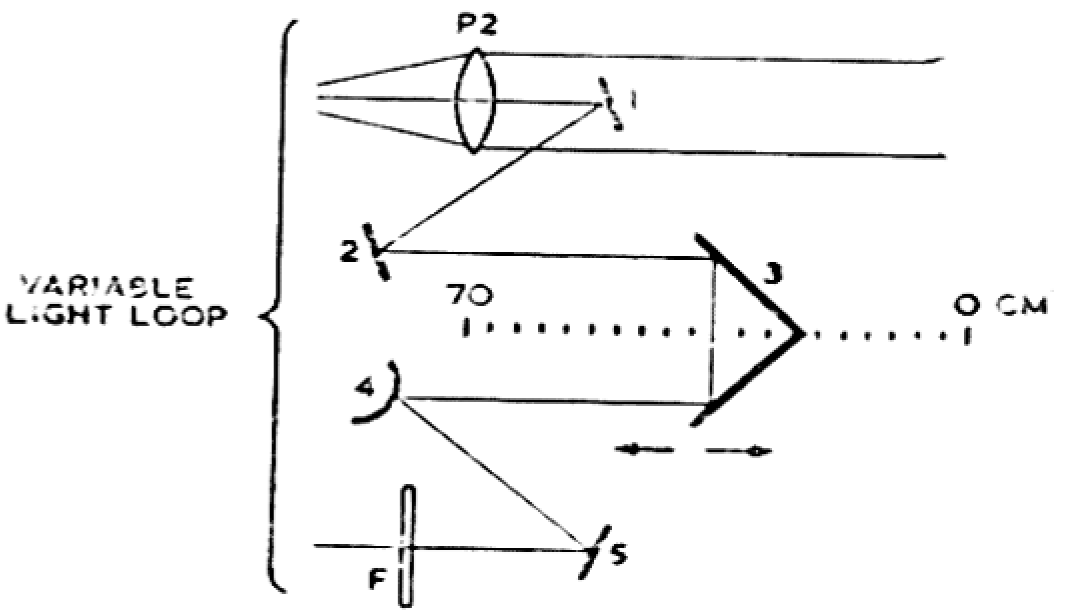


FIG. 17.6. Continuously variable "loop" of light.

The Influence of Atmospheric Conditions

Eq. (10) gives the velocity in air. To get the velocity in vacuum we have to take into consideration the influence of the refractive index μ of the air :

$$\mu=\frac{c}{V}\,, \tag{11}$$

where c is the velocity in vacuum and V the wave velocity in the actual medium. The measured velocity is a group velocity. Introducing an index μ_g corresponding to the group velocity we get :

$$\mu_g=\mu-\frac{d\mu}{d\lambda}\cdot\lambda \tag{12}$$

Ordinary dispersion formulae of the type

$$\mu = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \qquad (13)$$

will give with Eq. (12)

$$\mu_g = A + \frac{3B}{\lambda^2} + \frac{5C}{\lambda^4} \qquad (14)$$

Barrel and Sears give reliable data on μ. The effective wavelength of the filtered light being 5600 A., we get from Eq. (14)

$$\mu_g = 1.0003039 \pm 0.0000002 \qquad (15)$$

The variations of μ_g with wavelength λ, temp. $t^0\ C$, pressure p mm. Hg. and humidity e mm. Hg. are :

$$\frac{d\mu}{d\lambda} = 0{\cdot}55 \times 10^{-6} \text{ per } 100\ A. \frac{d\mu^{-6}}{dt} = -1{\cdot}0 \times 10^{-6}, \frac{d\mu_g}{dp} = +0{\cdot}4 \times 10^{-6},$$

$$\frac{d\mu_g}{de} = -0{\cdot}05 \times 10^{-6}. \qquad (16)$$

Final Computations

According to Eqs. (9, 10, 11, 12) we get the final equation for the velocity in vacuum to be :

$$c = \mu_g \cdot c_a \qquad (17)$$

or

$$c = \mu_g \cdot n \cdot \frac{4}{N} D_N\ . \qquad (18)$$

The frequency n was checked during the measurements by radio transmission to the frequency checking station of the Telegraph Service. The obtained values are assembled in the following table :

Date in 1949		Lamp voltage	Obs.	Weight	Vel : 299 790+	Temp. C°	Press
May	6	2.8	4	2.0	2.87	8	750
,,	8	2.8	6	12.0	3.56	1	755
,,	9	2.8	1	1.0	2.50	3	762
,,	10	2.8	7	5.0	2.63	9	765
,,	11	2.8	5	9.0	2.52	8	769
,,	13	2.8	5	3.0	3.52	11	765
,,	14	2.8	6	2.0	2.93	9	763
Sept.	24	5.0	2	0.5	2.84	11	768
,,	26	5.0	5	2.0	4.27	15	764
,,	27	5.0	5	5.5	2.68	12	763
,,	28	6.0	2	0.3	4.05	11	764
,,	29	3.5	5	7.5	2.84	14	758
Oct.	3	3.5	5	8.3	3.32	9	749

During all the spring season the visibility was good, but in the autumn, only on the two last days. No systematic influence of haze was observed. Probably a deepening red was compensated for by higher temperature of the lamp.

From the above table we get :

Mean of the spring values	289,793·04±0·19 km/sec.
Mean of the autumn values ...	299,793·10±0·20 ,,
Total mean	299,791·1 ±0·14 ,,

$$\left[\pm\sqrt{\frac{(pvv)}{(p)\cdot(13-1)}}\right]$$

The limits are obtained from the deviations from the mean. To get the real limits we have to consider the uncertainty of several external conditions.

The error in the colour determination has been set at 50 A. According to Eq. (16) this causes a relative error of $\pm\ 2{\cdot}8 \times 10^{-7}$. The mean error for the temperature will be less than ± 0·°2 C, that of the pressure less than ± 0·2 mm. and that of the humidity less than ± 1 mm. Hg. Thus arising from the influence of the atmosphere we get an error of $\pm\ 2{\cdot}5 \times 10^{-7}$. The mean error of the remeasured base line of 4×10^{-7} will be increased to 5×10^{-7} by including errors in the small actual added distances. The mean error of frequency will be less than 2 c/s or $\pm\ 2{\cdot}4 \times 10^{-7}$. Finally the position of the first zero-point contributes with an error of

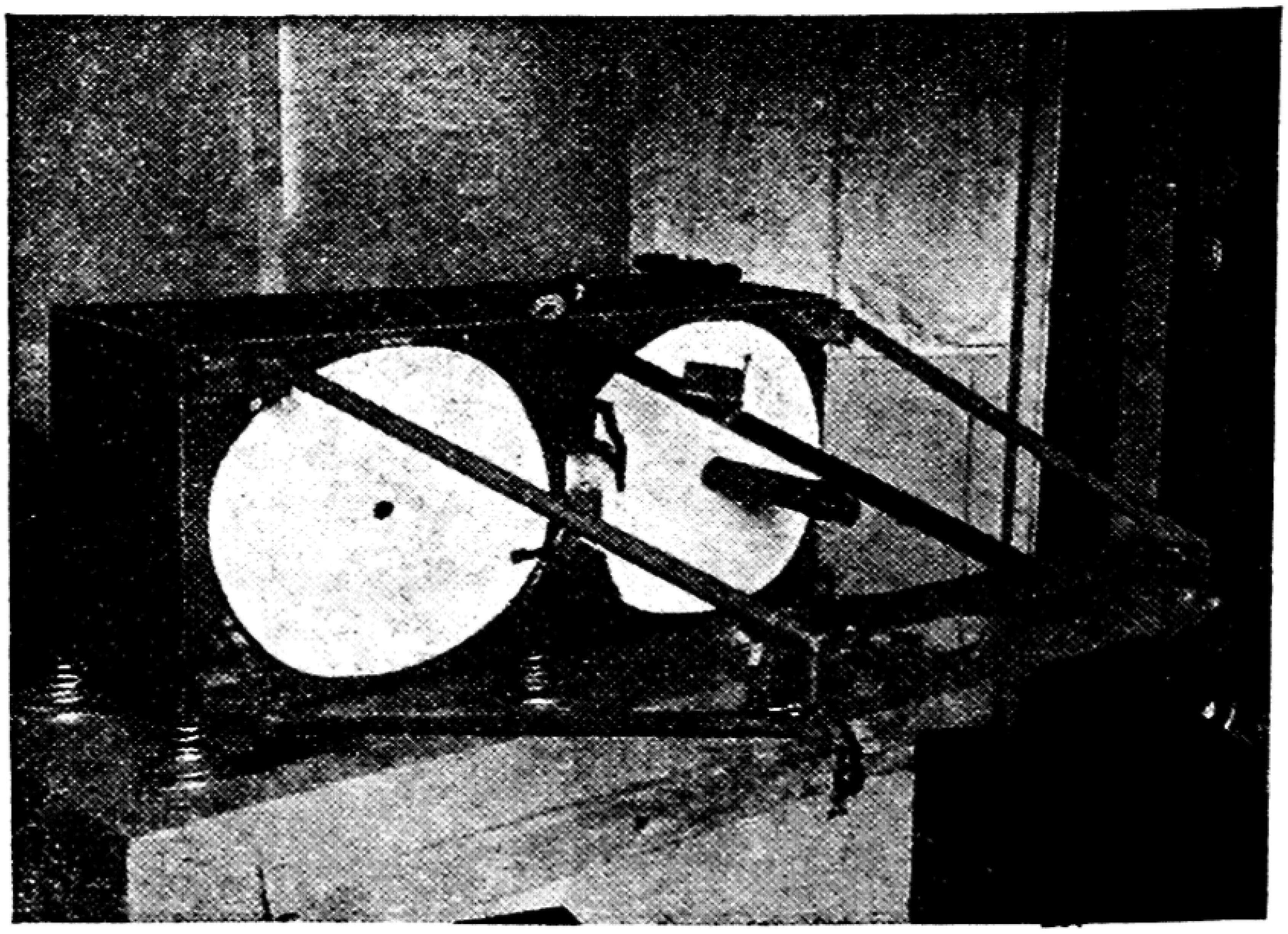


FIG. 17.7. General view of the geodimeter, the mirrors being replaced by white discs.

$\pm 3{\cdot}0 \times 10^{-7}$. Including the errors of the 769th zero-point and that of the refractive index we get a total $\sqrt{(vv)} = \pm 8{\cdot}80 \times 10^{-7}$.

As the final result of the determinations on the 7 km. base line we arrive at a velocity of

$$c = 299{,}793{\cdot}1 \pm 0{\cdot}26 \text{ km/sec.}$$

Values from other Base Lines

In 1948 the geodimeter was not yet complete, lacking the reversing commutators *SwI* and *SwII*. A preliminary determination, however, was made. With experience of the complete apparatus the values obtained in 1948 can now be corrected.[1] Likewise a determination with the first geodimeter of 1947 gives a value. In the following table all values are assembled :

Year	Distance	Weight	Velocity	Mean/ Mean/year
1947	11025±0.08	0.1	299 793.9±2.7	93.9
1948	4208±0.01	0.2	89.3±2.5	— 93.1
1948	9064±0.01	0.6	94.1±1.3	—
1949	1762±0.01	0.4	92.3±1.50	—
1949	5144±0.01	1.5	94.0±0.75	— 93.1
1949 May	6906±0.0035	8.0	93.0±0.27	—
1949 Sept.	6906±0.0035	8.0	93.1±0.28	—
		Mean :	299 793.1±0.25 km/sec.	

The error limits on the distances denote the geodetic accuracy.

Comparison with Determinations by Others

Michelson[2] (1926) obtained $c = 299\,798 \pm 4$ km/sec. Birge's statistical collation in 1942[3] gave the result $c = 299\,776 \pm 4$ km/sec. Essen's determination of 1948[4] by short radio waves in resonance in a short guide gave the value $c = 299\,792{\cdot}2 \pm 4{\cdot}5$ km/sec. (Essen gives ±9 as the maximum error.) Aslakson's value (1949)[5] by radar applied to six geodetically known distances in the U.S.A. is $c = 299\,792{\cdot}4 \pm 2$ km/sec., where the inner mean error of ±1·5 here has been increased to allow for possible systematic errors. Essen in 1950[6] obtained 299 792·5±3 km/sec. (max. error).

Determination of Lengths

As a practical application two uncertain first order sides in Norrland were determined.

(1) The distance between the islands of Prastgrundet and Storjungfrun near Söderhamn in August :

1st night :	20203·63	m. (One obs.)
2nd night :	20203·57±0·04	m. (Six obs.)
Mean :	20203·59±0·04	m.

The coordinates give 20203·79 m. However the length as determined from the new Söderhamn base line via a base net and two triangles is 20203·25 m. Supposing this value to be of double the weight of that from the coordinates, the geodetically determined length would be 20203·43 m. which is in tolerable agreement with the value determined with light.

(2) The distance between the two fields Ounistunturi and Sautusvaara near Kiruna in Lappland in September :

1st night	30921·67 ± 0·17 m.	Two obs.	Weight 1
2nd night	30921·52 ± 0·05 m.	Ten obs.	Weight 3
3rd night	30921·37 ± 0·07 m.	Five obs.	Weight 2
Weighted mean	30921·50 ± 0·07 m.		

The frequency was checked as usual. Provisionally adjusted coordinates gave the distance 30921·42 ± 0·60 m.

In the Norrland measurements and with 1762 m. base line, the geodimeter was supplied with tension from a portable 400 watts benzene motor generator. For the rest the 230 volts grid was used.

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SOMMAIRE

SUMMARY

L'experience de Fizeau qui a permis la mesure de la vitesse de la lumière peut maintenant servir à mesurer les distances. Nous avons bien entendu à connaître d'abord la vitesse de la lumière.

Une cellule de Kerr et un photomultiplicateur sont alimentés en H.F. (8 Mc/s), le générateur de tension comportant en particulier un crystal de quartz. La cellule de Kerr permet de moduler la lumière. Un miroir plan à la distance D km renvoie le faisceau vers la cellule receptrice. La sensibilité photoélectrique du récepteur étant modulée on obtient un courant qui varie periodiquement avec la distance D. Si l'on module la tension à 50 cycles par second le courant en haute fréquence change de phase 100 fois par seconde. Un instrument récepteur qui traduit le courant photoélectrique subit des deviations exactement symetriques par rapport à l'axe des x.

La position des points 0 peut être definé avec une précision supérieure à 1 cm. pour $D=10$ km. Si l'on connait D on peur calculer λ et la vitesse en résulte d'après la relation $c=n\lambda$. La variation de vitesse est de 10^{-6} par degré C. et de $0{\cdot}4\times10^{-6}$ par mm. de mercure pour la pression atmosphérique. Les résultat obtenu à l'aide d'une base de 7 km. comparé à ceux obtenus pour d'autres distances, a été, pour la vitesse dans la vide :

$$c=299{\cdot}793.1\pm0{\cdot}24 \text{ km/sec.}$$

Toutes les erreurs sont envisagées dans la mesure où elles sont connues. Utilisant la valeur précédante, une base d'environ 30 km. a été mesurée ; on a trouvé 30 921·47±0·07 m.

L'appareil (" geodimètre ") pèse 250 livres et fonctionne à l'aide d'une lampe de 400 W, le courant étant obtenu à l'aide d'une groupe electrogène à moteur à essence. On étudie un modéle plus léger comportant deux fréquences de modulation.

Inverting Fizeau's principle for determination of the velocity of light, distances can be measured. First, however, we have to determine the velocity of light.

A Kerr cell and a phototube are supplied by high frequency (8 megacycles) emission from a crystal controlled transmitter. By the Kerr cell the intensity of an emitted light beam varies periodically. A plane mirror at a distance of D km. reflects back the beam against the phototube. The high frequency varying sensitivity of the tube being more or less timed to the entering light variations, we get a photocurrent, the magnitude of which varies periodically with increasing distance D. By an imposed 50 cycle tension the high frequency light variations shift their phase 100 times a second. An indicating instrument, controlled by the photocurrent, gives deflections exactly symmetrical with respect to the O-axis.

The position of the zero points can be assigned more accurately than ±1 cm. at D=10 km. If D is known we get λ. The frequency n being known too we get the velocity according to $c=n\lambda$.

The variation with atmospheric temperature is 10^{-6} per degree C. and with pressure 0.4×10^{-6} per mm Hg.

The result from a 7 kms. base line and with control from other distances was, after transforming to vacuo

$$c=299\,793.1 \pm 0.24 \text{ km./sec.}$$

All errors, so far as they are known, are considered.

Using c and after three nights of measurements a 31 km. distance was found as

$$30\,921.47 \pm 0.07 \text{ m.}$$

The apparatus used, the "geodimeter," is 250 lb. in weight and operated by a 400 watts benzene motor generator. The prototype of a lighter 100 watts model having two frequencies n is being developed.

DISCUSSION

DR. L. ESSEN said that towards the conclusion of the late war he became interested in methods of measuring the velocity of propagation of short electromagnetic waves and the measurement, which was of importance in connection with radar and other radio applications was accordingly undertaken at the National Physical Laboratory. Waves were introduced by a probe into a cylindrical metal cavity only a few inches in diameter and length closed by a flat plate at each end and the frequency adjusted until resonance occurred. The velocity so obtained was 16 km./sec. greater than the accepted value. Further experiments with an adjustable resonator (exhibited to the audience) confirm the original value and it is particularly pleasing that Mr. Bergstrand's value agrees with the N.P.L. value to within ½ km./sec. Direct radar measurements in the U.S.A. agree within 1 km./sec.

SIR CHARLES DARWIN had noticed a curious phenomenon that in the determination of fundamental constants a number of observers at about the same time obtained closely similar answers. Then the value changed appreciably but several observers still obtained closely similar results of the new magnitude.

DR. A. MARECHAL observed that it was understood that the frequency in Mr. Bergstrand's measurements would be checked against astronomical time measurements, but would like to know how the distance was compared with the standard metre.

MR. E. WILFRED TAYLOR said that a six-mile base-line had recently been measured in England, by the usual methods, to an accuracy of about 2 parts per million. How did this compare with estimates by Mr. Bergstrand's method ?

MR. BERGSTRAND replied that the distances involved in his experiments were determined by normal geodetic methods, ultimately involving comparison with the standard metre. The accuracy was estimated at one part in two million. It was other errors of similar order which together raised the estimated error in the velocity of light to nearly one part in a million. On a base-line of six miles the accuracy of measurement by the geodimeter would be about one part in two million. It would be necessary to wait for clear weather, but given that condition the observations could be completed within a week.

18. Apparatus for the Photometry of Optical Instruments

J. GUILD
(National Physical Laboratory, Great Britain)

The photometry of an optical instrument comprises all quantitative measurements which may be required to determine the fraction of the incident light from any part of the object field which is utilised in the formation of the image or to determine the effect of multiple reflection or scattering within the instrument in producing unfocused glare light in the field.

Such measurements are relevant to the performance of all kinds of optical instruments, including even plane windows, but they are of special importance for telescopes and photographic lenses, and it is the tests developed at the National Physical Laboratory for instruments of these types which are to be described here.

We have found it convenient to make the complete test of an instrument in three separate operations in which are determined

(*a*) *The paraxial transmission factor*, or ratio of the emergent and incident light-fluxes in a paraxial pencil sufficiently narrow to pass through the instrument without interference by any of the stops.

(*b*) *The field-brightness distribution*, or ratios of the brightness of the image field at different distances from the centre to that at the centre when the object field is uniformly bright.

(*c*) *The veiling-glare index*, or fraction of the apparent filed brightness, under specified conditions, which is due to unfocused light.

By combining the information derived from (*a*) and (*b*) the effects of light losses in the instrument and of restriction of the aperture of inclined pencils by vignetting at the stops on the apparent brightness of any part of the field can be obtained, while (*c*) indicates the loss of contrast which the image will suffer from stray light caused by multiple reflections or by optical inhomogeneities or dirty surfaces.

Description of Apparatus

Paraxial Transmission Factor

The same apparatus serves for telescopic systems or photographic lenses. It is shown diagrammatically in Fig. 18.1. *G* is a 48 watt headlight lamp. An enlarged image of the filament is formed at a diaphragm *S* consisting of one or other of a set, shown separately at the top right hand of the diagram, ranging from 0·5 mm. to 2·5 mm. in diameter, mounted in a slide. The most convenient size of diaphragm depends on the magnification of the instrument under test.

The small hole at *S* is at the focus of a collimating lens L_3 of 12·5 cm. focal length, and 2 cm. diameter, fitted with an iris diaphragm, *I*, to control the cross sectional diameter of the beam leaving the collimator.

The telescope under test is mounted coaxially with L_3. On looking through it, the bright hole in the focal plane of the collimator is seen, and the alignment of the telescope is adjusted to bring this to the centre of the field. With many instruments the clear aperture exceeds that of the collimator lens, and the whole of the beam passes through the telescopes without interference by stops, but if not, the iris *I* is closed down until the beam has a clear passage. The transmitted beam leaves the eyepiece with a divergence depending on the magnification of the telescope and the angular size of the hole at *S*. The ratio of the total light in the emergent beam to the total light in the entering beam is the transmission factor of the telescope as no light has been prevented from passing by stops.

To measure the emergent light, an integrating sphere, Fig. 18.2, of 6 inches diameter, with an aperture, *A*, of 2 cm. diameter, is used. The sphere is mounted on a portable stand provided with horizontal and vertical adjustments, and can also be rotated about the vertical diameter of the aperture *A*. A rectifier photocell C_2 is fitted to an aperture opposite *A*, and a circular disc, *E*, about 3 cm. in diameter is mounted by means of a thin supporting rod in the middle of the sphere. The interior of the sphere and both sides of *E* are nickel plated and thickly coated with magnesium oxide. A filter *F* is provided to serve the double purpose of raising the colour-temperature of the light to that of daylight and correcting the spectral sensitivity of the photo-cell to that of the eye.

This sphere is placed with the aperture *A* near the eyepiece of the telescope and lined up so that the emergent beam enters *A* centrally and falls approximately centrally in the disc *E*. The alignment at *A* is made by covering *A* with a piece of very lightly ground glass. The cross-section of the beam is seen on this screen and the outline of the aperture is seen quite well through it. The iris *I* is adjusted to make the beam definitely narrower than the aperture, so that it has a clear entrance. The ground glass for this purpose is mounted on an arm so that it is easily inserted for checking the adjustment and then removed. The intercept of the beam by the disc *E* can be observed through a small aperture *H*, fitted with a lens of 3 inches focal length. If, owing to the divergence, which depends on the angular diameter of the object-hole at *S* and the magnification of the telescope, the cross section of the beam at *E* is too large to be contained by the disc, a smaller hole has to be used at *S*. The most satisfactory adjustment, which can be attained in much less time than it takes to describe it, is one in which the beam enters *A* with a clearance of two or three millimeters all round, and the illuminated patch on *E* leaves a margin of at least five millimeters.

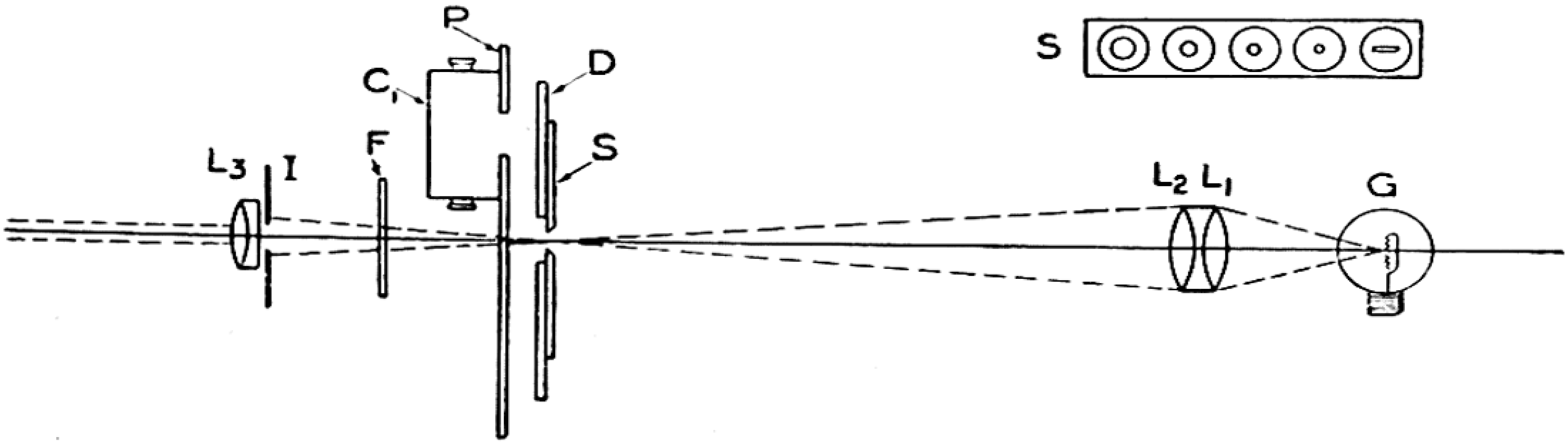


FIG. 18.1. Apparatus for measurement of paraxial transmission factor.

When the sphere has been adjusted the light is shut off by a rotating shutter *D*, shown, as seen from the left, in Fig. 18.3. This shutter snaps into any one of three positions. In position 1, it gives a clear passage to the light beam; in 2 it cuts this off and enables the zero reading of the galvanometer in circuit with the photocell to be observed or set. In position 3 another aperture in the shutter disc, backed by a second photocell, C_1, connected in parallel with C_2, is opposite the object-hole. The purpose of this is described later. With the light shut off the galvanometer zero is observed. The shutter is then moved over to admit the light, and the amount of this is indicated by the response of the photocell C_2 as indicated by the galvanometer deflection. Denote this by δ_1.

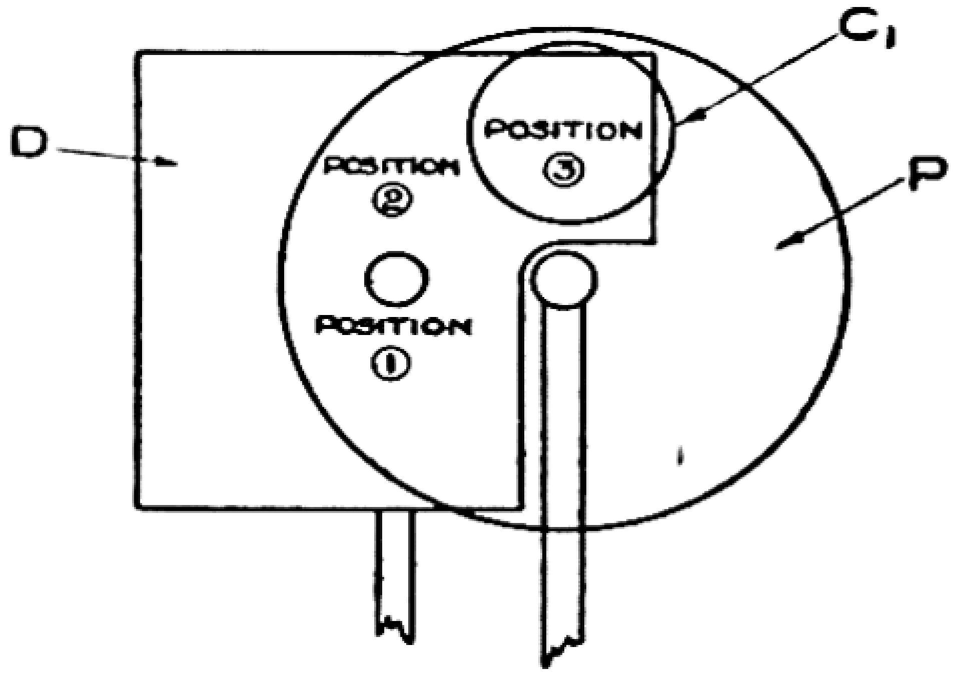


FIG. 18.2. Integrating sphere for measurement of emergent light in the apparatus of Fig. 18.1.

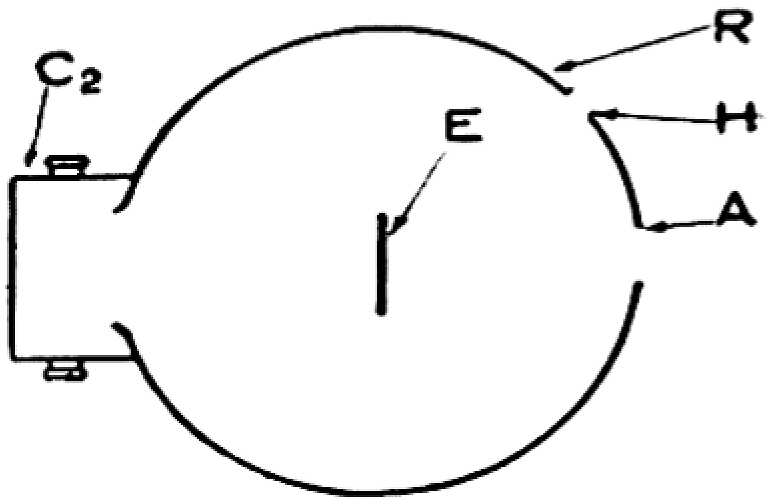


FIG. 18.3. Front view of sphere showing rotating shutter *D*.

The telescope is now removed, the portable sphere brought up to a few centimeters in front of the collimator lens L_3 and adjusted so that the beam enters *A* and impinges somewhere on *E* as before. The galvanometer zero is again checked and the deflection, δ_2, which now measures the total light in the beam leaving the collimator, noted. The ratio δ_1/δ_2 is the required transmission factor of the telescope.

There are some practical details which require to be noted. It facilitates work, by saving unnecessary calculation, if the galvanometer scale reads directly in percentage transmission. To do this the current through the lamp is adjusted, in relation to the size of object hole and beam diameter at *I* which is in use, so that the deflection δ_2, corresponding to the incident beam intensity is exactly 100·0 millimeters. If, when observing δ_1, the galvanometer zero is not merely noted but is set to be exactly zero on the scale, as is easily done by sliding the scale parallel to itself, the deflection δ_1 gives the percentage transmission directly.

With binoculars or other small telescopes there is not much time interval between the observations with or without the telescopes, but with large heavy instruments, such as periscopes or rangefinders, the services of a team of labourers may be necessary to put the instrument into position and to remove it after δ_1 has been observed. In these cases, the time interval between the two observations may be considerable, and it may be unwise to rely on the intensity of the beam remaining unchanged for this time. This is where the photocell C_1 comes in. If the shutter disc is brought to the third position the light from the object hole is intercepted by C_1. This results in a galvanometer deflection ,δ_3, say. If this is done just before or after every observation with the sphere it provides a check on the constancy of the incident light. If the intensity changes during the interval between the observations with and without the telescope the change is revealed by taking a reading of the beam intensity C_1 and can be corrected by readjusting the lamp current until the original deflection δ_3 is restored. This direct check on beam intensity is not only more convenient than checks of the voltage and current of the lamp but is more reliable, as it detects any changes in beam intensity which may arise from other causes than change of electrical input of the lamp.

Tests can be performed very rapidly with this apparatus. The actual observations take only a few seconds, the bulk of the time required for a test being taken in shipping and unshipping the instrument.

A slight correction, amounting at the worst to about 0·5%, has to be made because of non-linear response of the photocell. The accuracy of the measurements of transmission is about 0·2%.

Fig. 18.4 gives a general view of the apparatus. The lamp house and condensing lens are visible at the far end. Facing us, just above the middle of the picture is the shutter disc with the auxiliary photocell attached, and in front of that the collimating lens from which the test beam emerges. The instrument under test—in the picture it is a monocular gun-sighting telescope of a Naval pattern—is mounted on a suitable support on a stand provided with adjustments for tilt and slew. This in turn sits on a larger table which can slide transversely on the rails seen on the left. This enables an instrument to be pushed out of the way, while the incident beam is measured, without disturbing its adjustment so that it can be brought back into position without requiring realignment if it is desired to repeat the test. The integrating sphere, with the photocell C_2, is shown in position for receiving the light emerging from the eyepiece. When the instrument is pushed out of the way the sphere is moved close up to the collimator to measure the beam intensity.

This apparatus can, of course, be used to measure the transmission factors of photographic lenses, or of separate components of optical instruments such as object glasses, prisms, eyepieces, etc. It can also be used to measure the reflectances of mirrors.

Distribution of Field Brightness

The brightness of the image field depends not only on the transmission factor of the instrument but also on the effective aperture of the image forming pencils. The transmission factor along the different paths traversed by pencils from different parts of the field varies very little from the paraxial value. The variation of brightness across the field is due almost entirely to variation in the effective aperture of the pencils due to vignetting by the limiting stops. In measuring the variation we must therefore utilise all the light comprised in the pencils illuminating each point in the field. For reasons which will become apparent it is convenient, when making the measurement for a telescope, to make the light traverse the instrument in the wrong direction. Light being reversible if we direct the eyepiece end of the telescope to a field of uniform brightness, the same pencils will convey the flux which is destined for any point in the original object plane that conveys the flux *from* that point when the instrument is the normal way round. It follows that if the eye were large enough to take in the whole pencil from the objective the distribution of apparent brightness in the field of the reversed telescope would be the same as in its field as normally used. The arrangement at present used for this determination is shown diagramatically in Fig. 18.5.

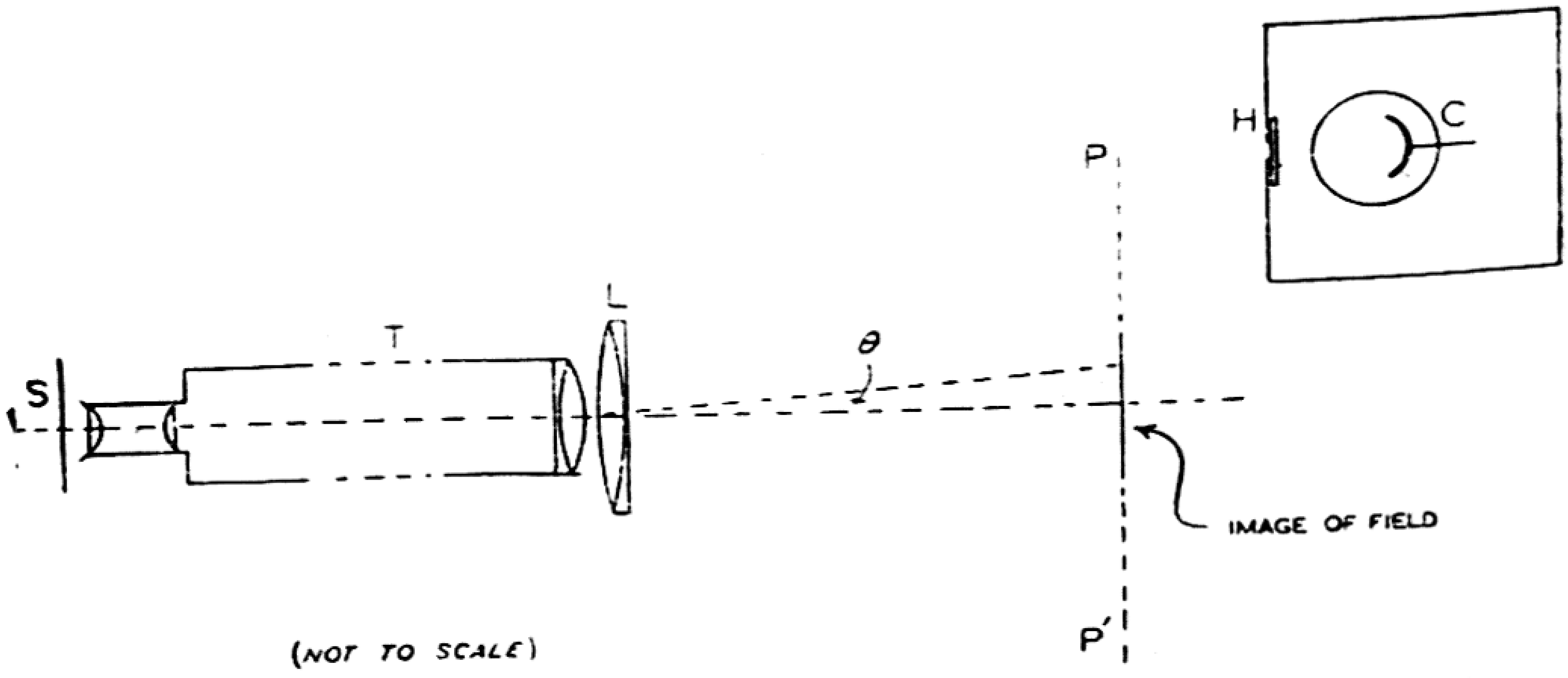


Fig. 18.5. Apparatus for measurement of field brightness distribution.

A uniformly bright source, S, is placed at the exit pupil of the telescope, T, under test. An auxiliary lens, L, of larger diameter than the object glass is placed in front of it. An image of the field, bounded by the image of the field stop, is formed in the focal plane, PP' of this lens.

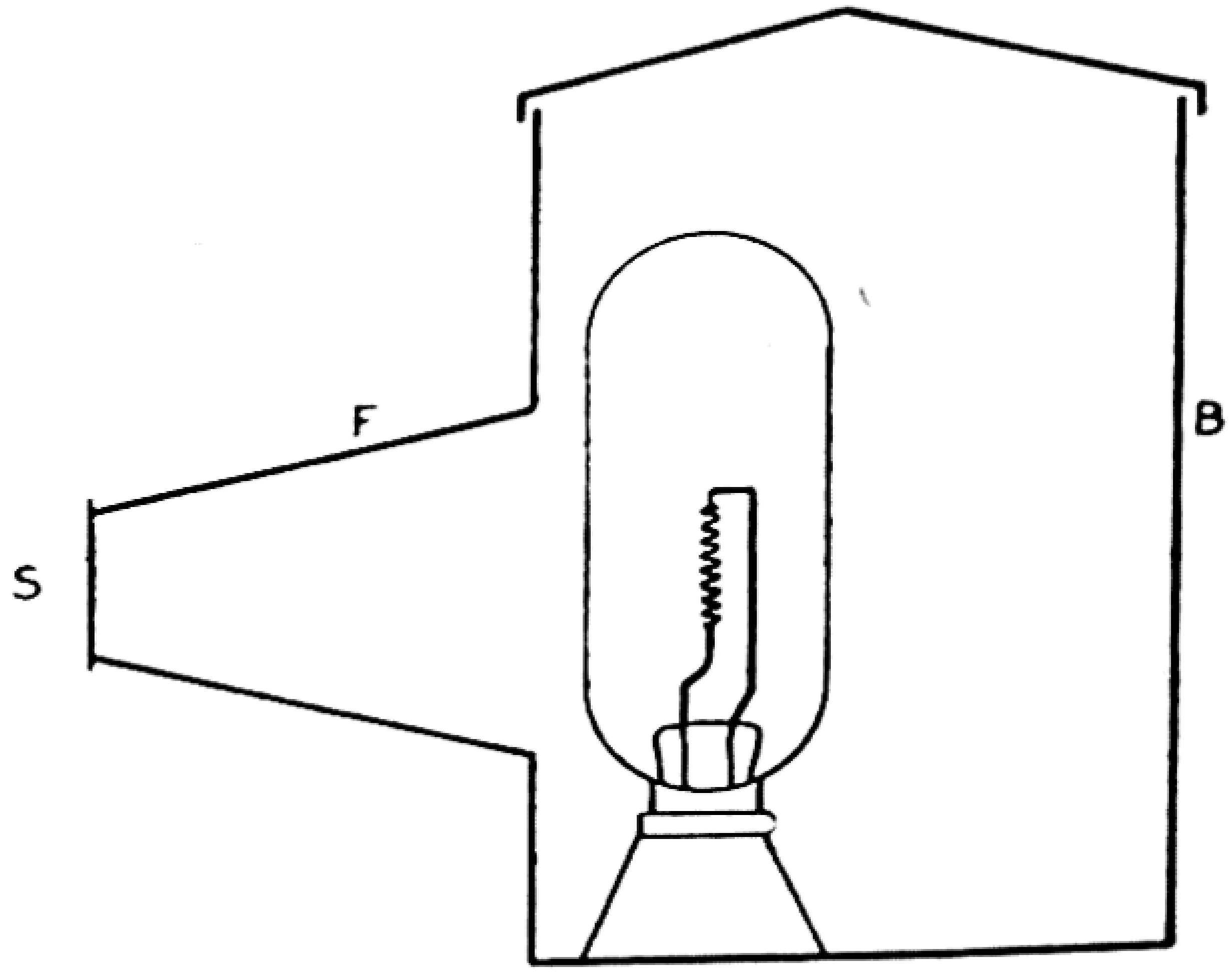
The pencil going to any point in the field has its cross sectional area on emergence determined by the effective aperture for that point. If a screen is placed at PP' to receive the image its illumination at any point is uniquely related to the brightness of the corresponding point of the apparent field. The total light per unit area in a small element surrounding any point in this image is measured by a photoelectric receiver shown separately at the right of the figure. This consists of a photocell, C, mounted in a box with a small bevelled diaphragm, H, backed by a translucent diffuser—a thin sheet of opal glass or of Ilford diffusing medium. The box is mounted with the diaphragm H in the plane PP^1 and is provided with horizontal and vertical adjustments by means of which the aperture can be brought to any part of the image of the field. The response of the cell is proportional to the light per unit area received by the diffusing screen behind the diaphragm. The ratio of the cell responses at different distances from the centre of the image to its response at the centre is measured. It is easily demonstrated that if ρ_θ is the value of this ratio for a point in the field corresponding to an inclination θ to the axis in the object space the ratio of the field brightness in this direction to that at the centre when the telescope is used in the normal way and directed to a uniformly bright sky is $\rho_\theta/\cos^4\theta$. Alternatively we can regard this as the ratio of the brightness of any object when viewed at an angle θ from the centre of the field to the brightness of the same object when brought to the centre.

Errors of one or two per cent at the margin of the field are of little consequence in this measurement, so in the great majority of cases we can neglect the division by $\cos^4\theta$ which does not affect the result by one per cent. until the radius exceeds 3½ degrees. A large proportion of telescopes have fields less than this.

With regard to practical details, a convenient source of light is shown in Fig. 18.6. S is a sheet of Ilford diffusing medium or thin pot opal glass at the narrow end of a funnel, F, projecting from a cylindrical lamp house, B, containing a 500 watt gas-filled lamp of projector type. The interior of the lamp house and funnel are coated with good quality matt white paint. With this arrangement the screen *S* is very uniformly illuminated and its emission obeys Lambert's Law over a wide angle. Its brightness is of the order ⅓ to 1½ candles per sq. cm., depending on the voltage applied to the lamp.

The lens, *L*, should be of such focal length as to give a field image of from 5 to 10 cm. diameter. Several alternative lenses are necessary to suit various patterns of telescope. They should be thin lenses, free from colour. High optical quality is not required.

FIG. 18.6. Suitable lamp housing for use with the apparatus of Fig. 18.5.



The photocell should be of the emission type with a single stage D.C. amplifier. Rectifier cells are not sensitive enough to permit the use of a very small aperture at *H*. The diameter of *H* should not exceed 1/30th of the diameter of the field image. The smaller it is the more closely do the results apply to definite points in the field. It is not necessary to provide a filter to simulate the spectral response of the eye as the effect of wavelength on the amount of vignetting in a given direction is negligible. Distances from the centre of the field are most easily determined as fractions of the field radius. This is a convenient method of measuring displacements from the axis in a telescope where the field stop provides a sharp boundary to the field. To facilitate the determination of the fractional radius at which each measurement is carried out the face of the photometer box on which the image is formed is marked with horizontal and vertical millimeter scales centred at *H*. *H* can then be brought to the centre of the field with great precision by adjusting it horizontally and vertically until the right and left edges of the boundary, and also the top and bottom, are equidistant from the origin of co-ordinates. The horizontal and vertical diameters are noted—the

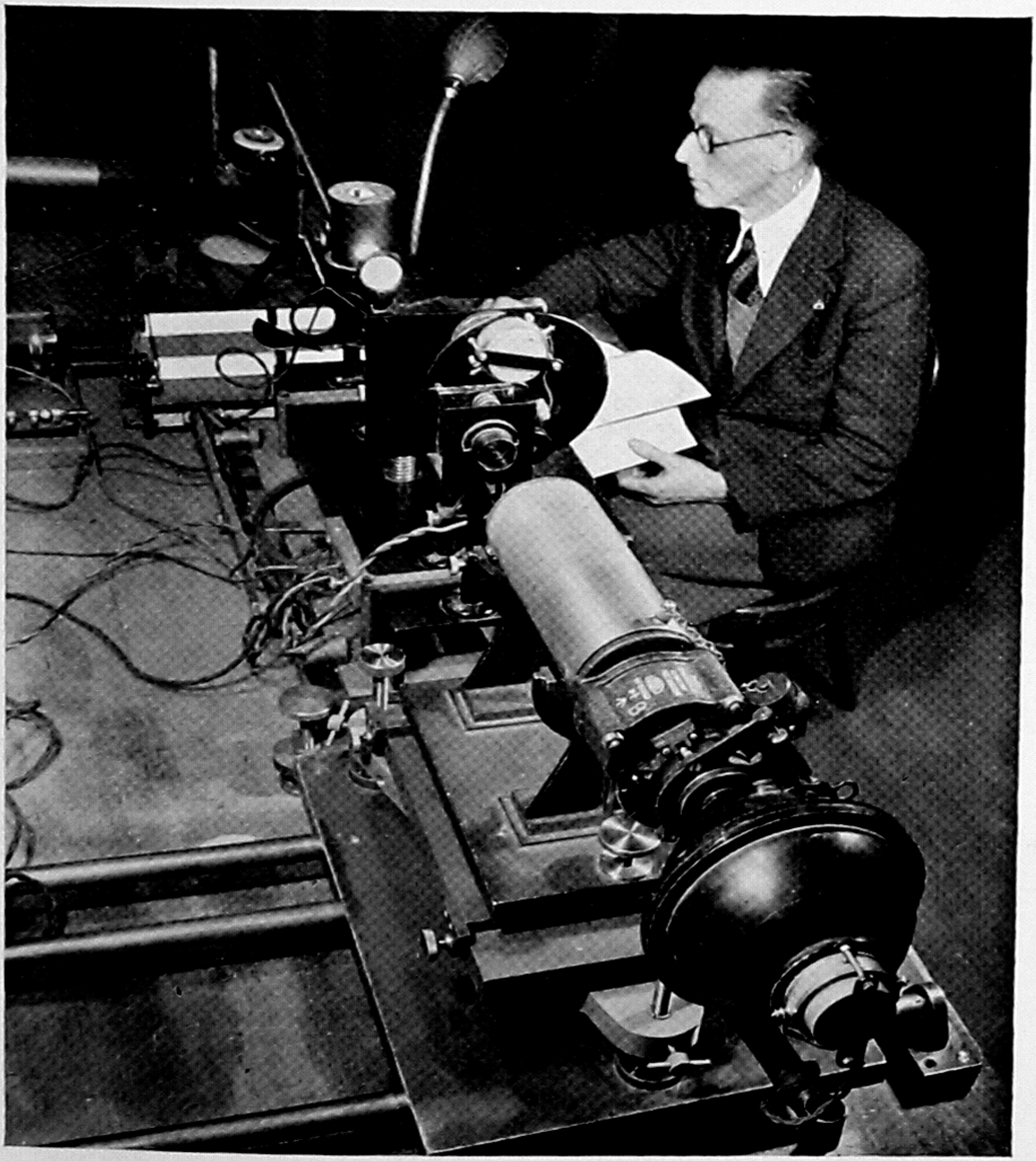


FIG. 18.4. General view of apparatus for measurement of transmission factor.

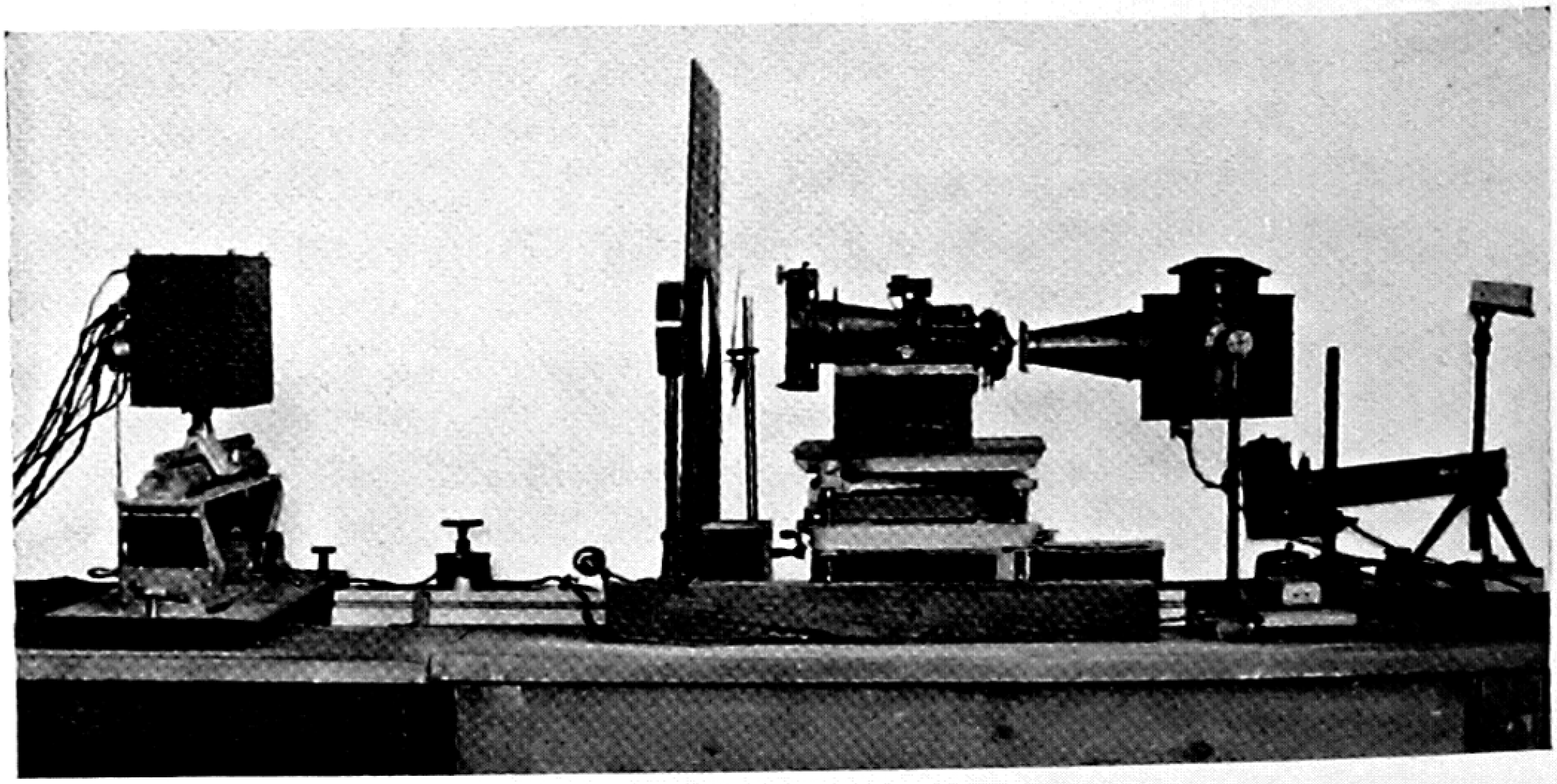


FIG. 18.7. Measuring field brightness distribution of a telescope.

field may not be quite circular—and it is then a simple calculation to find the fractional radius for any other position of H during a horizontal or vertical traverse. For example, if the boundary readings on the horizontal scale when H is at the centre of the field are + 28·1 mm. and —28·1 mm. and if the readings during one of the off-centre measurements are — 20·3 and —35·9 the fractional radius of the point where the aperture is now located is (28·1 — 20·3) /28·1 or + 0·28. This is a more convenient method of locating the point of measurement in practice and, also, of picturing the characteristics of the brightness distribution, than one in which the displacement is specified in angular coordinates.

From a knowledge of the angular radius of the field the fractional displacements are readily convertible to angles where required for application of the cosine correction.

The advantages of testing the telescope in the reversed direction will now be apparent. The equivalent "sky" illumination being provided at the exit pupil of the telescope instead of at the entrance pupil the source of uniform brightness need not be large. A small source of uniform and high brightness is much easier to construct than a large one, and the same serves for all telescopes whatever may be the diameter of their object glasses. Further, the variation of θ from the centre to margin of the field is small, making the cosine term either negligible or small enough to be evaluated from rough estimates of the angles. With the telescope the other way round not only would large angles of incidence on the image screen be involved, requiring careful evaluation of the cosine term, but any appreciable departure from Lambert's law in the diffusion by this screen would affect the peripheral measurements.

It will be obvious that the measurements obtained as described above give the distribution of field brightness on the assumption that the full aperture of the telescope is effective. Many telescopes, when used by daylight, have their limiting aperture determined by the size of the observer's pupil. In such cases, if the distribution applicable to daylight vision is required, a diaphragm of the appropriate pupillary aperture must be mounted at the place normally occupied by the observer's pupil, or alternatively, a diaphragm of m* times this diameter may be mounted in the neighbourhood of the object glass.

Fig. 18.7 shows the actual apparatus. The principal features from right to left are :—the illuminating lantern ; the telescope under test (one barrel of a binocular gun-sight) ; the photoelectric photometer box mounted on a support which provides both horizontal and vertical movement, the former by sliding along the triangular bench and the latter by the rapid screw control of the height of the adjustable table to which the bench is attached.

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* m being the magnification of the telescope.

The cell used is a " Cintel " V.B.26 (bismuth-silver-caesium cathode) built into a single-stage valve bridge amplifier contained in the photometer box. The bridge is balanced with the shutter cutting off the light from the telescope and the out-of-balance currents caused by exposure to the field are measured by galvanometer deflexions.

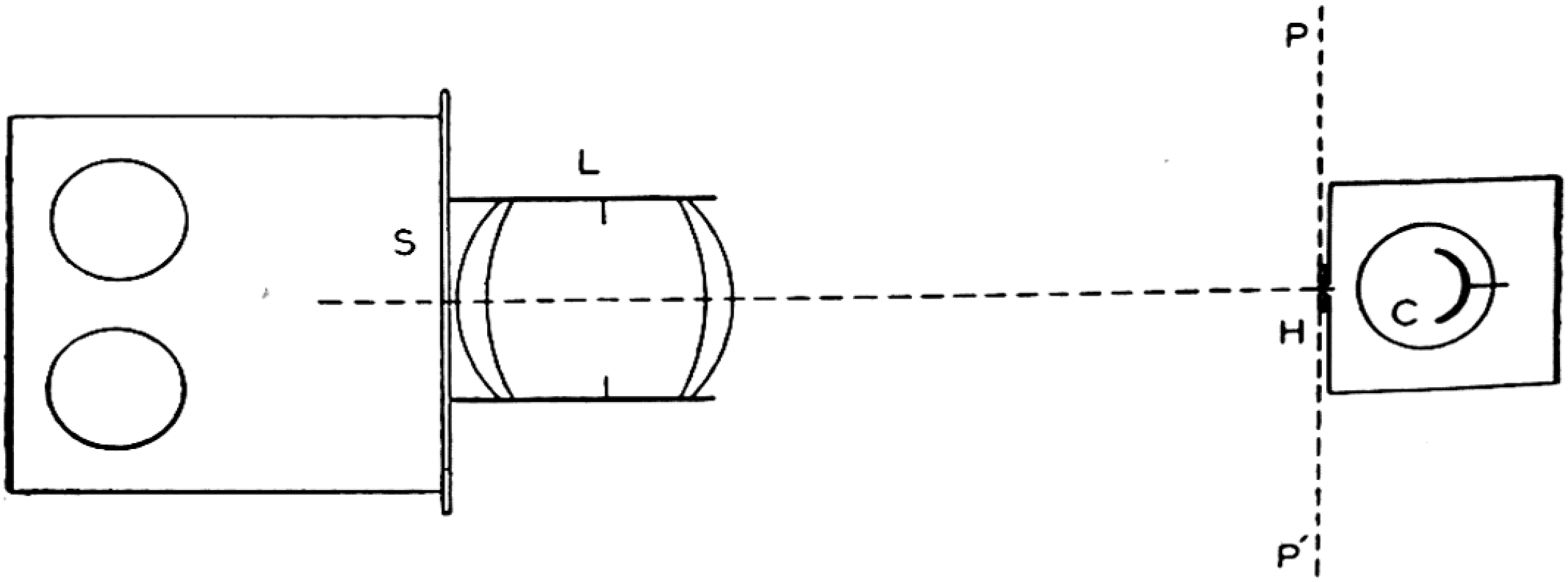

Fig. 18.8. Apparatus for measurement of variation of plate illumination in a photographic lens.

With photographic lenses we are concerned with the variation of plate illumination from the centre to the margin. This can be determined photographically but this method is tedious and full of pitfalls for any but photographic experts. A non-photographic method is preferable. Several such methods are used, but some of them are faulty in principle through neglect of the possible difference between the image-space directions and the directions of the pencils incident on the plate. Any method in which the quantities obtained in the test have to be corrected by cosine terms introduced arithmetically should be avoided because it is not always easy to determine with sufficient precision the angles whose cosines are involved. The method I prefer is shown in Fig. 18.8. *L* is the lens under test, and *PP′* is its focal plane, where the plate will normally be situated. A uniformly illuminated diffusing screen *S* is placed against or close to the front end of the mount. In this position the screen is equivalent to a luminous surface of infinite extent or a uniformly bright " sky " anywhere in the object space. All rays from the luminous surface which reach any point in the plane PP^1 leave the surface in the same direction and meet the first refracting surface in a parallel beam just as if the luminous plane were at a remote distance. All we do by bringing it up against the lens mount is to avoid the need for an infinitely large source at infinity.

The same photo-electric photometer that serves for testing telescopes for field brightness variations will also serve here. When using this photometer for the telescope tests the diffusing screen at *H* is mounted behind the diaphragm so that the plane of the front of the box can be in the focal plane to receive a sharp image of the field stop, but there is no sharp boundary to the field of a photographic lens, so this consideration does not arise. On the other hand, when making measurements towards the edge of the plate the angles of incidence are high and the effective area of the small aperture may be reduced appreciably if the bevelled edge is not of razor sharpness. This difficulty does not arise with telescopes because of the small angles of incidence involved, but can be serious at the larger angles in the photographic lens test. For this test it is better to have the diffuser in front of the hole, Ilford diffusing medium should be used rather than opal, and the diffusing surface should be outermost. This surface should be in the focal plane. There are two ways in which the test can be carried out, and the one which is preferable depends on what auxiliary apparatus is most readily available. In one method the cell box is mounted rigidly on a support which can be moved along a horizontal slide perpendicular to the axis, the plane of the small aperture at *H* remaining parallel to the image plane during traverse. The absence of a defined boundary to the field makes the fractional radius method of estimating position inapplicable. The axial point must be determined by some appropriate alignment test and other positions measured, in the first instance, as distances from the centre of the plate. These can be converted to angular displacements if desired.

The alternative method gives the displacements directly in angular measure. It requires a nodal slide bench.

The lens is adjusted so that its back nodal point coincides with the nodal axis of the bench. The illuminated diffusing screen *S* and the lamp or lamps used with it must be mounted on a fitting which rotates with the lens so that their relative positions remain unaltered. The photometer box is mounted in a fitting attached to the member which represents the plate on the nodal slide, the test aperture (*H*), being located at the centre of the plate when the angular scale reads zero. Then on setting this scale to some other angle, the nodal slide linkage maintains the perpendicularity of the lens axis to the face of the photometer box, at the same time so changing their separation that the same relative configuration of lens and photometer is produced as would result from a corresponding movement of the photometer in the plane of the plate in the first method.

Each of these methods has advantages. For lenses of medium focal length there is little to choose between them, but for those of short focus, such as are used for cinematography and in an ever increasing proportion of hand cameras, the second method has some advantage in convenience over the first. On the other hand when one of the large long focus lenses sometimes used for air photography has to be tested neither the lens itself nor the illuminating gear can conveniently be accommodated on normal nodal slide equipment and the first method has to be used.

Veiling Glare Index

In every optical instrument some stray light, arising from multiple reflections at surfaces or from scattering by inhomogeneities in the optical media or by scratches or dirt on the surfaces, finds its way to the image plane, where it is visible as a more or less diffuse haze and reduces the apparent contrasts of the true image. The amount of stray light and its distribution in the field of any given instrument depends on the distribution of brightness in the object field. If the field contains a concentrated source of great intensity compared with other objects in the field, the stray light will be very strong in the zone immediately surrounding the image of this source, falling off rapidly in all directions. Other objects near the source may be rendered completely invisible—the familiar phenomenon of glare associated with bright sources. At the other extreme, if the object field is uniformly bright, each element is surrounded, in the image plane, by a glare pattern similar to that from a concentrated source, but the superposition of the glare patterns from all the elements of the field results in a uniform distribution of the glare light, except quite near the margins of the field. Fields of intermediate character will show a distribution of glare light intermediate between these two extremes. A field of average character not containing the sun or other localised source of high intensity will have a moderately uniform distribution of glare light over comparatively large areas. This appears as a mist or veil superposed equally on the darker and lighter portions of the various objects in the field which are consequently seen with reduced contrast. In this country the term " veiling glare " has been given to this generally distributed stray light.

No optical system is quite free of it, but instruments differ considerably in the amount they introduce, either on account of their design or, among instruments of the same design, on account of differences in cleanness or quality of materials or workmanship. The property of an instrument which determines how much veiling glare it will produce in given field conditions is clearly important. For some users of the instrument it is much more important than the attainment of high quality in the optical imagery to which the attention of designers is almost exclusively directed.

Telescopes

The importance of veiling glare in telescopes was first recognised during the recent war and the National Physical Laboratory was asked to devise a simple and rapid quantitative test by which instruments could be graded with respect to this property. The method of test which proved most convenient is illustrated in Fig. 18.9.

A Fullolite lamp 1, with a bulb 10 cm. diameter, and rated 150 watts, is mounted in a lantern 2. A large double condenser lens 3 focuses a magnified image of the lamp in the plane of a collimator objective, 4, of 60 cm. focal length and 9 cm. diameter, whose focal plane is a few millimetres in front of the nearest surface of the condenser. The image of the lamp is several times larger than the lens 4, so the aberrations of the condenser do not affect the distribution of light within the aperture of 4. Seen through 4 the condenser appears uniformly illuminated and is equivalent to a zone of sky of angular diameter about 20 degrees. By means of a series of circular diaphragms, such as 5, which can be mounted centrally in front of the condenser, smaller sky zones can be obtained. An opaque, blackened, circular disc 6, is supported by a very thin wire 7 on the axis of the condenser. The disc can be removed from the field by rotation about a pivot (not shown in the diagram) at the lower end of the supporting rod. Several discs, of diameters from 3 to 12 mm., are provided. A black screen surrounding the lens mount prevents stray light from passing the plane of the

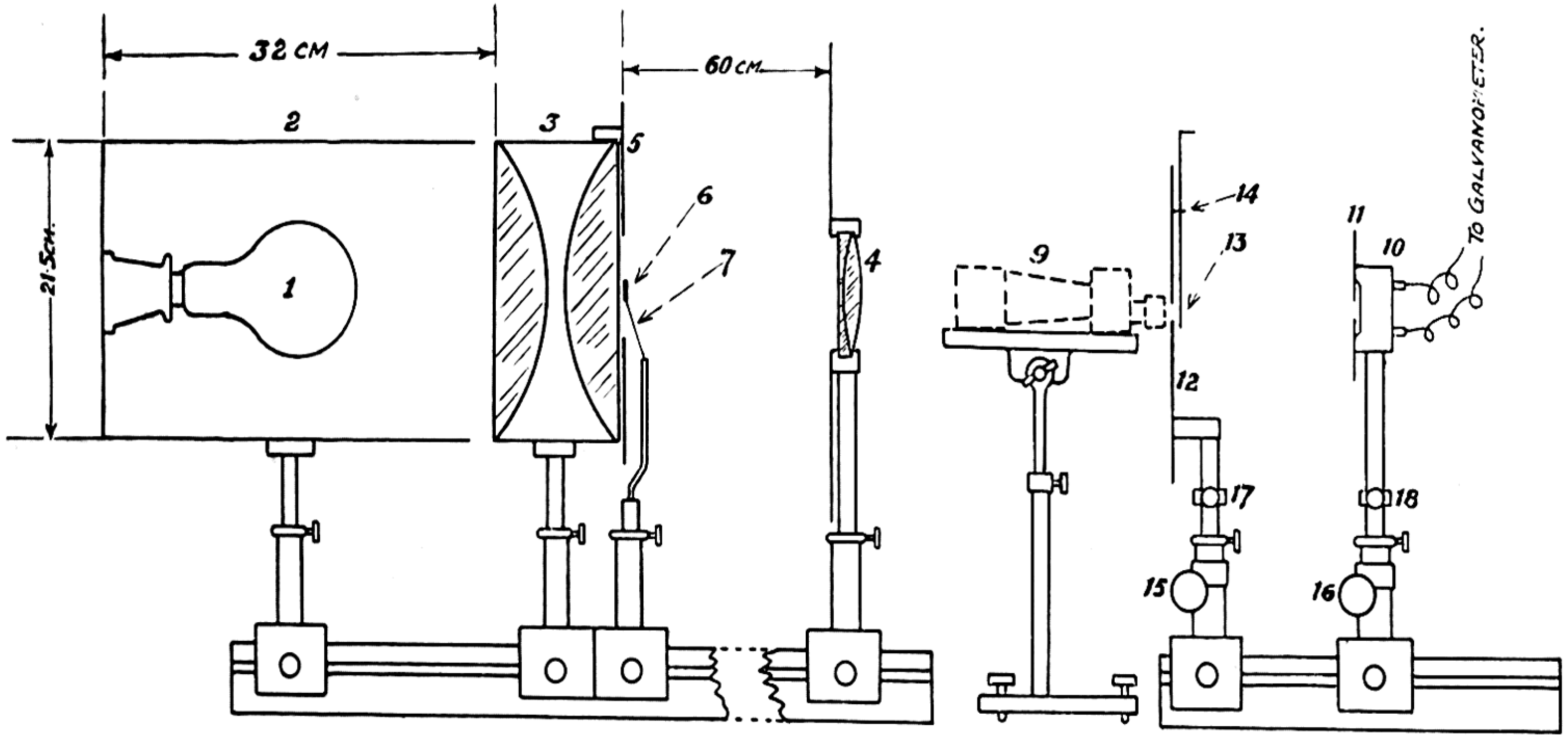

FIG. 18.9. Layout of apparatus for measurement of veiling glare in telescopes.

1. 150 W. lamp.
2. Lamp housing.
3. Condensing lens.
4. Collimator objective.
5. Circular diaphragms.
6. Opaque circular disc, supported by wire, 7.
9. Binocular under test.
10. Selenium rectifier photo-cell, with diaphragm, 11.
12. Diaphragm in front of eyepiece.
13. Aperture shutter, pivoted at 14.

15, 16, 17, 18. Height adjustments.

collimating lens. The lamp, condenser, disc, and collimator objective are supported on an optical bench, of familiar type, which can be fixed down to a table.

The telescope under test is supported on a separate adjustable stand, and is set approximately coaxially with the collimator. One barrel of a binocular is illustrated, 9. On looking through the telescope the disc 6 will be seen as a circular dark object, and is brought to the centre of the field by adjusting the telescope.

If the telescope were entirely free from veiling glare, the image of the disc would be perfectly black but in the presence of veiling glare it has an appreciable brightness. The ratio of this brightness to the brightness of the surrounding field is independent of the absolute values and is adopted as the index of the veiling glare from which the instrument suffers. It has been named the *veiling glare index*, or more briefly the *glare index*, and is denoted by *g*. The veiling glare in the field of a telescope depends on the extent of the bright area to which it is exposed, *i.e.* on the angular diameter of the zone from which light is incident on the object glass, and also on the diameter of the dark spot within which the glare is estimated. In general the glare index is increased by increasing the diameter of the bright zone or by decreasing the diameter of the dark spot.

The measuring apparatus is seen on the right of the telescope in the diagram. A selenium rectifier photocell, 10, has attached to it an opaque screen, 11, with a circular aperture, 1 cm. diameter, in the centre. The aperture is bevelled at the back and the screen has a matt reflecting surface in front.

A diaphragm 12 is placed in front of the eyepiece of the telescope, and a shutter 13, consisting of an opaque disc about 25 mm. diameter attached to a light support which pivots about the pin 14, can be set either to cover the aperture in the diaphragm or leave it open.

The diaphragm and the photocell are carried on a short length of optical bench, which can be moved about on the table to bring the parts which it carries into approximately the right position relative to the telescope. Coarse adjustment for height is effected by raising or lowering the supporting rods in the saddle-stands: fine adjustment by a rack and pinion movement incorporated in the saddle-stands and operated by the drums 15, 16. Approximate adjustment of alignment is effected by moving the whole measuring unit on the table and fine adjustment in a direction perpendicular to the plane of the sketch by means of screw activated slides 17, 18, inserted between two lengths of the supporting rods. These vertical and transverse adjustments enable the diaphragm 12 and the entrance aperture of the photocell to be set concentrically with the axis of the beam emerging from the telescope eyepiece.

A test is conducted as follows : With the shutter open, the eyepiece is focused to form a real image of the field, with its central black disc, on the screen 11, the distance of the latter being adjusted at the same time (by moving the saddle-stand along the optical bench) until the diameter of the focused image is about 20 per cent greater than that of the cell aperture. The width of this overlap is not critical : it can be adjusted closely enough by estimation.

The shutter 13 is now closed and the circuit of the galvanometer and photocell is completed. After the zero reading of the galvanometer has been noted, the shutter is opened and the new reading of the galvanometer taken. The difference between these readings measures, on an arbitrary scale, the average brightness of the image of the black spot over the area covered by the photocell aperture.

The shutter is again closed, and the disc 6 swung out of the field. Galvanometer readings with the shutter closed and open are again taken, their difference giving, on the same scale as before, a measure of the field brightness. The ratio of the deflexions with and without the spot in position is the required glare index.

The effect on the measured value of the glare index of the size of the black disc depends to some extent on the particular causes of the veiling glare in each instrument—the location and curvatures of the reflecting surfaces ; the nature and location of the scattering elements, and the polar distribution of the scattered light—but examination of a large number of telescopes with discs of different sizes showed that, on the average, the glare index with a disc of 0·2 degree diameter is about 1·5 times that with a disc of 1·0 degree. For the purposes of a standard test one disc must be adopted and early tests showed that for the great majority of Service telescopes a diameter of 1·0 degree is convenient. This disc size is therefore assumed in values of veiling glare index measured at N.P.L. except in special cases, *e.g.* instruments of high power and correspondingly small field, when a smaller disc must be used and its diameter specified.

The value of the index depends also on the angular diameter of the surround field and some standard diameter has to be used if results are to be comparable. Here again the choice is arbitrary and the value adopted—8 degrees—was based on convenience in testing large numbers of naval binoculars. These arbitrary conditions have to be varied when, for one reason or another, they are obviously inappropriate, but in all cases where there is no good reason for another choice an eight degree surround field and a one degree black disc are used.

As the glare is due to light which has been diverted from the direct optical path through the telescope it is not obliged to pass through the exit pupil, and the photocell may receive some light which has passed outside the exit pupil. But this light would not get into the eye of a person using the telescope and so would not contribute to the veiling glare in the apparent field. To exclude this unseen glare from the measurement an iris diaphragm is fitted to the aperture of the shutter plate and adjusted to be in the plane of the exit pupil. A Ramsden eyepiece, mounted on a hinged support, can be swung into position for viewing the iris and the exit pupil when making this adjustment. The iris can be set to represent any size of eye pupil, but here, again, a standard condition has to be prescribed for normal tests and a pupil diameter of 7 mm. is chosen unless there are special reasons to the contrary.

When testing clean instruments in which the veiling glare index is low a sensitive galvanometer is required in order to get a usefully large deflexion from the image of the black disc. The deflexion with the disc removed is then too large for the scale. To meet this difficulty a neutral filter with a transmission factor of about 10% is mounted on a hinged fitting on the shutter plate and can be swung into the beam to reduce the larger deflexion in a known proportion.

A further modification is required with telescopes having fixed focus eyepieces which cannot be racked out to form a real image of the field at the photocell. With these it is necessary to place near the iris diaphragm, on the side nearest the cell, a spectacle lens of suitable focal length to give the correct size of image of the black disc at a convenient distance. The power required depends on the magnification of the telescope under test. This lens should be mounted eccentrically so as to use a peripheral portion where the surfaces are inclined to each other and to the telescope axis, to prevent a fictitious addition to the veiling glare by multiple reflections between the surfaces of the auxiliary lens or between them and the surfaces of the eyepiece.

Fixed focus telescopes were relatively rare until recently and have hitherto been treated as special cases ; but there is a tendency to adopt fixed focus in an increasing number of Service instruments, and the incorporation of the auxiliary lens technique is tending to become normal practice.

The actual apparatus is shown in Fig. 18.10.

Some typical values of the glare indices obtained from these measurements may be of interest. A clean new binocular telescope of the 6 surface type may have a glare index between 1 and 2 per cent., the average being 1·4%. For an ordinary ×6, 12 surface, type the average value is about 2·2%. Some more complicated Service telescopes have indices several times as great as this. Deterioration of surface condition in use or during storage in unsuitable climatic conditions may raise these values considerably in a few months. The glare index may rise to 3 or 4 per cent. without the instrument appearing noticeably dirty. Values as high as 10 to 15 per cent. have been found in some binoculars returned from service at sea. These however do look foul, and vision through them is extremely poor.

The practical importance of veiling glare in a telescope depends on the nature of the work for which it is being used. It becomes important when a large part of the field is of much greater brightness than the region containing the objects of interest. This condition arises when trying to make out the identification markings or other features of aircraft in flight when, as is usually the case, the near side of the machine is in comparatively deep shadow compared with the surrounding background of sky. It frequently happens that the objects which it is important to see are in a shadow region of very low brightness level compared with large regions of sky or fully illuminated terrain which form part of the surrounding field. The veiling glare due to these extensive bright areas, though only a small percentage of the average field brightness, may be quite large relative to the average brightness within some localised region in shadow.

Suppose the average brightness of the surrounding scene to be 100 units so that the veiling glare, in an instrument whose glare index is 5%, is 5 units. If now there is a local region within which the illumination is only a fiftieth of the average over the field, the highest brightness in this region is 2 units, while the lowest—that of a black object—is, of course, zero. But when 5 units of veiling glare are added to these, the maximum apparent contrast within the shadow region is that between areas of brightness 7 and 5 units respectively, and the whole range of contrasts is compressed within these limits.

Many intermediate and low contrasts which would be quite conspicuous in the absence of veiling glare are reduced below the limit of perception and so are just wiped out. A ration of 50 : 1 between the general brightness level of the field and the local brightness level within some region of special interest is by no means extreme. Much greater ratios often prevail in the everyday use of telescopes, and veiling glare from the brighter portions of the field may be enough to obliterate the whole range of contrast within the shadow region.

It is clearly of the first importance to establish a correlation between the amount of veiling glare in a telescope and its efficiency as an aid to vision. The investigations we have made on this matter are outside the scope of this paper, but as an indication of the significance of the test figures of veiling index the difference in performance of a telescope with an index of 1% and another with index 2% can just be detected by a critical observer when observing detail within deeply shaded regions. For less severe tasks considerably greater differences in veiling glare index are undetectable by the user.

As a rough working rule, any telescope whose index does not exceed the normal for clean new instruments of its pattern by more than 1½% for normal values less than 3%, or by more than 2% for instruments with higher normal values, can be regarded as a good instrument of that pattern. If the excess over the normal exceeds these figures the instrument will not be as satisfactory, in some circumstances of observation, as a normal instrument.

Photographic Lenses

Some aspects of glare in photographic lenses have long been familiar to photographers. The glare spots which are apt to appear on photographs taken when the sun or some other very bright light is shining from the front are known to most people who carry a camera around. Very similar effects on the plate are sometimes produced by light reflected from the edges of the folds of the camera bellows and are not due to the lens at all; but glare spots often do originate in the lens and their nuisance value is well known. But we do not have glare spots in every photograph and we can avoid having them at all if we care to abstain from photographing scenes with the sun in front of us. But the more widely distributed veiling glare originating not in highly concentrated light sources but in the integrated effect of all the bright elements of the field is present in every photograph and we cannot avoid it. Because it does not show up as a localised blemish on the picture it escapes the notice of most people and, until the war, had not received much attention. No systematic method of evaluating the glare producing property of a lens had been developed. It is obvious that a veiling glare index of similar significance to that applied to a telescope can be assigned to a photographic lens, and many lenses were tested on this basis at N.P.L. during the war. But while the same criterion can be employed—the ratio of the brightness of the image of a black disc in the centre of a uniformly bright field to the brightness of the field—the same experimental arrangements are not suitable. In testing telescopes it is possible to use a test field not much greater than the field of view because, owing to a telescope being a long narrow system with most of the optical elements well inside the body tube, the effects of light from directions outside the field of view in producing glare is relatively unimportant. Photographic lenses, however, are short squat systems in which the posterior components are not so well hidden from oblique zones of the frontal hemisphere as are those of a telescope. We may therefore expect that zones of considerable obliquity will contribute quotas to the veiling glare and it would not be safe, as a basis of comparison of lenses of different types, to limit the size of the test field, at least until we have some idea of the consequences of doing so. It appeared from the analysis of tests of various types of lens that a test field of about 80 degrees angular diameter is necessary to give the same reliability of comparison as is obtained with the 8 degree field for telescopes.

To provide a uniformly bright field of this extent in apparatus suitable for lenses of all sizes is a matter of great difficulty, and for accurate results I prefer an indirect method which, though somewhat tedious, provides a complete analysis of the glare properties of the lens.

Since the veiling glare at any point of the image is simply the sum of the contributions of all the minute elements of the field, each acting as a glare source, the essential property of a lens which determines veiling glare under all conditions is the distribution of glare from a small source.

Consider the effect of a small source of light, situated in a direction inclined to the axis, in producing veiling glare at the centre of the image plane. Apart from the small source the object field is supposed to be perfectly dark. The image of the source is formed off the axis, so no direct light can reach the centre point, which should receive no illumination. But some of the indirect light distributed in various directions by multiple reflections and scattering in the lens may reach the centre and produce a certain illumination of the plate in this neighbourhood. The most convenient way of expressing the magnitude and character of the effect of a glare source is by the equivalent background brightness, and it is this apparent luminosity falsely imparted to the field which constitutes veiling glare. If we measure the equivalent background brightness at the centre of the field for all inclinations of the glare source to the axis we have all the information we require to predict the veiling glare at the centre of the field for any distribution of light sources in the field, including as a special case the close packed distribution of small sources which make up a continuous uniform field. Obviously we could choose any point in the field at which to measure the effect, and a complete analysis of the glare quality of the lens would have to include exploration of the background brightness at every point in the field, but for test purposes the glare at the centre serves to grade the lens with respect to this property.

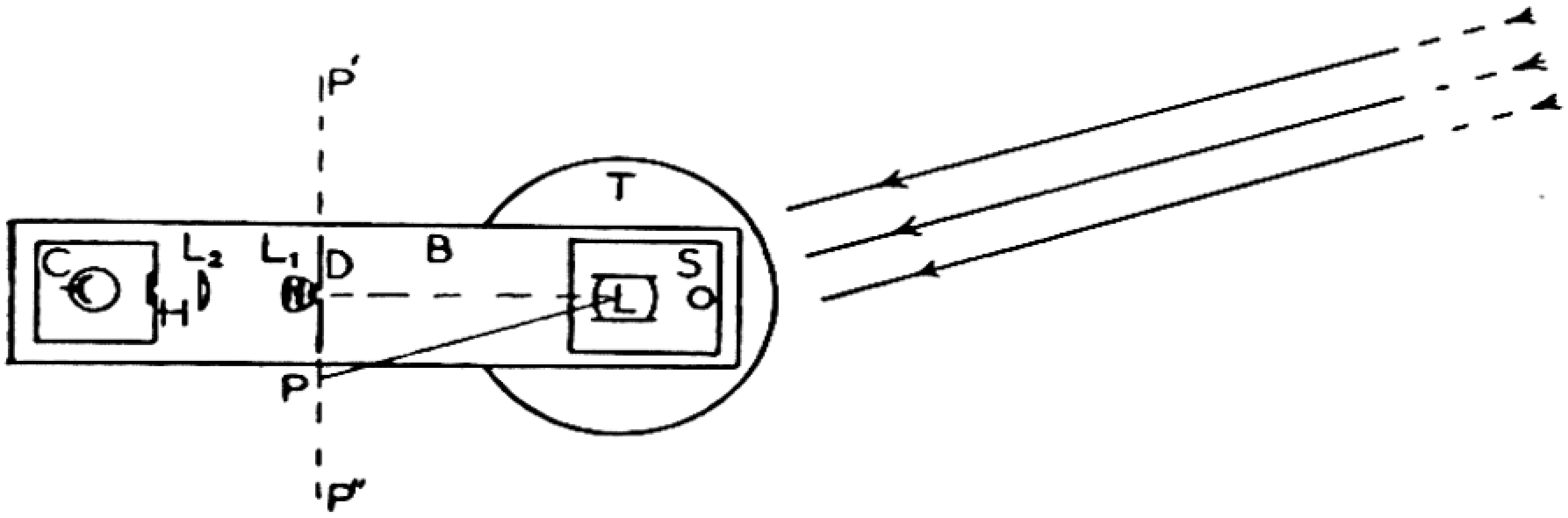

FIG. 18.11.

The method used for measuring the equivalent background brightness at the centre of the field for different directions of the glare source is shown in Fig. 18.11.

L is the lens under test. It is mounted on adjustable *V* supports on a base *S*, which is located by hole, slot and plane on a rigid table, *B*, 8 inches wide, and as long as may be required for the job. This is bolted to a turn-table *T*, which consists of a dividing head from a milling machine. This provides a more robust support for the unbalanced load of the measuring equipment than any spectrometer table or similar rotor made for laboratory use, and is easily and smoothly rotated, by means of a worm drive, without disturbing the alignment of the apparatus on *B*. Adjustments on the support *S* enable the lens to be aligned with its axis horizontal and parallel to the centre line of the table and its back nodal point in the axis of rotation. A diaphragm *D* with a small accurately cut and bevelled aperture is placed in the focal plane $P'P''$ of the lens. Light from a 1000W. projector lamp at a distance of 10 yards or more, depending on the focal length and aperture of the lens under test, comes from the direction indicated by the arrows. By rotating the turntable the lens axis may be set at any inclination to the incident beam. In the position shown, the directly transmitted beam proceeds in the direction *LP* and the aperture at *D* is illuminated by the veiling glare at the centre corresponding to the source angle *DLP*. An image of the aperture is formed by the lens combination L_1L_2 on a diffusing screen behind the aperture *H* in the box containing a photocell *C*. The aperture *H* is 1 cm. in diameter. The diaphragm *D* is a rotatable disc with a series of 10 apertures of diameters approximately 1, 2, 3 . . . . 10 millimeters. The one used depends on the focal length of the lens under test, but whichever is used the lens L_2 and photocell box are adjusted so that its image is smaller than the cell aperture *H*. L_1 is a wide angle triplet, of short focus, resembling an Abbe substage condenser only larger. It is necessary for this lens to have a larger aperture ratio than the photographic lens under test in order that it may collect the whole of the cone of glare light coming from *L* to *D* and condense it all within the aperture of L_2 which then transmits it to the photocell.

The indication of the cell is then a measure of the veiling glare on the axis when the incident light is in the direction *LP*. The measurement is repeated at a sufficient number of inclinations (by rotating the turntable) to determine a graph showing the equivalent background brightness on the axis for all directions of the source. The lens being symmetrical about its axis the results apply indifferently to inclinations in any plane.

The actual apparatus used is shown in Fig. 18.12. The features already mentioned will be easily recognised. The lens under test is seen above the centre of the turntable. The rotatable aperture plate faces it, with the hole which is in use at the top. The aperture plate and the wide-angle condenser, part of which can be seen projecting from behind it, are supported as one unit on a " T-square" slide which enables it to be moved to any required position along the table without lateral or angular readjustment. Beyond is seen the second focusing lens which feeds the light to the aperture of the photocell unit. When making a test various diaphragms and curtains, supported by frames, one of which is shown in the photograph, are fitted to shield the cell from any light other than what comes through the lens under test. The graduated wheel, with handle, is the worm drive for the turn-table. For the measurements just described it is operated by hand. The chain drive which can also be seen is for another purpose.

The background brightness diminishes rapidly at first as the source moves away from the axis, the rate of diminution slowing up as the inclination increases. Advantage can be taken of the slow variation at high obliquities to use a larger aperture at the collecting point than is suitable at the smaller inclinations where the curve is steep, the results being corrected by factors inversely proportional to the areas of the holes used.

The results thus obtained, though proportional to the equivalent background brightness for the various angles of incidence, are on an arbitrary scale of photocell responses. It is convenient to express them as the ratio of the equivalent background brightness to the illumination which the source produces at the lens. We require for this a measure of the illumination on the same arbitrary scale. In this connection we have to remember that although the veiling glare originates at various places inside the lens, the concept of equivalent background brightness locates the " veil " in the object space. The light from the veil is deemed to have passed through the lens by the same paths, subject to the same losses in transmission and aperture restriction, as light from the true objective field in the region where the glare is being measured, *i.e.* at the centre of the field in the present case. It is convenient, therefore, to evaluate the illumination from the source by some method which eliminates the transmission factor and the aperture of the lens, since, although those are both measurable, it is desirable, where possible, to keep the measurement of one property independent of the measurement of others.

There are several ways in which this can be done, the following method requires less auxiliary calibrated apparatus than the alternatives.

The turntable is set so that the source is on the lens axis. A sheet of Ilford diffusing medium is inserted normally in the incident beam, about a tenth to a fifth of the distance from the lamp to the lens and faced, on the side nearest the lens, with a circular diaphragm of such a size that its image on the aperture disc in the focal plane is from 2 to 3 times the size of the acceptance aperture which is in use, so that the latter is completely covered by the image with something to spare all round. When making these adjustments the photocell should be protected from accidental excessive illumination from the image of the unscreened lamp by inserting an opaque card between the acceptance aperture and the cell aperture. When the adjustments are made another card should be mounted to intercept the light before it reaches the lens and the first one removed. This second card serves as the shutter for the actual measurements.

Let d_1 and d_2 be, respectively, the distances from the lamp to the diffusing screen and to the lens, and denote by k the diffuse transmission factor of the screen for light at normal incidence.

Let a_s be the area of the acceptance aperture at the centre of the image plane when this calibration measurement is being made and let x_s be the photocell response.

It can be shown that the scale factor we require is

$$F = \frac{a_s d_2^2 k}{x_s d_1^2 \pi}. \tag{1}$$

If, in measuring the glare from the source in direction θ the area of the acceptance aperture is a and the photocell response is x_θ the quantity

$$\beta_\theta = \frac{x_\theta}{a} F \tag{2}$$

is the ratio of the equivalent background brightness of the veiling glare when the source is in the direction θ to the illumination at the lens, *i.e.*, the equivalent background brightness per unit of illumination.

β_θ is termed the veiling glare factor of the lens for direction θ.

It will be noted that in this method of evaluating the scale factor it is unnecessary to know the transmission factor of the lens, its aperture, or the distance of the exit pupil from the image plane. The only quantities to be measured, apart from the cell responses, are the distances d_1 and d_2 and the transmission factor k of the diffusing screen. This factor is easily determined by various methods

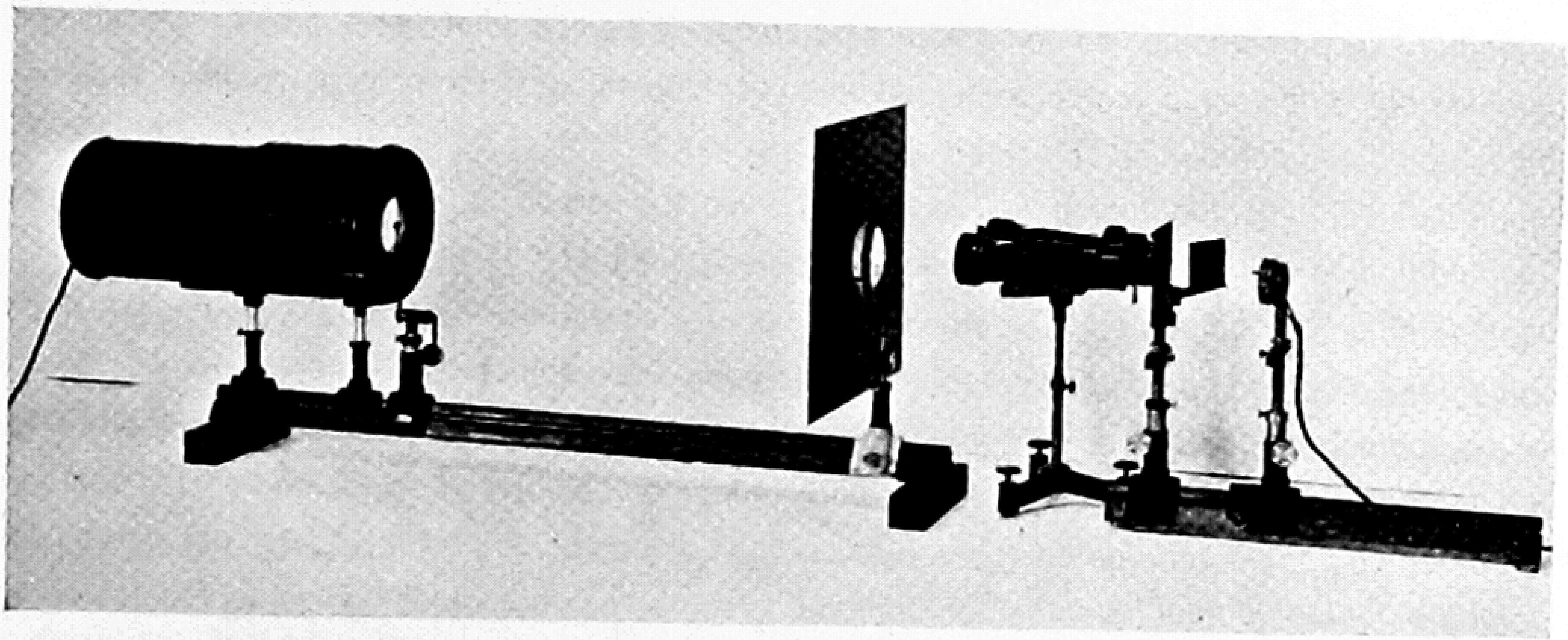

FIG. 18.10. View of apparatus shown diagrammatically in Fig. 18.9.

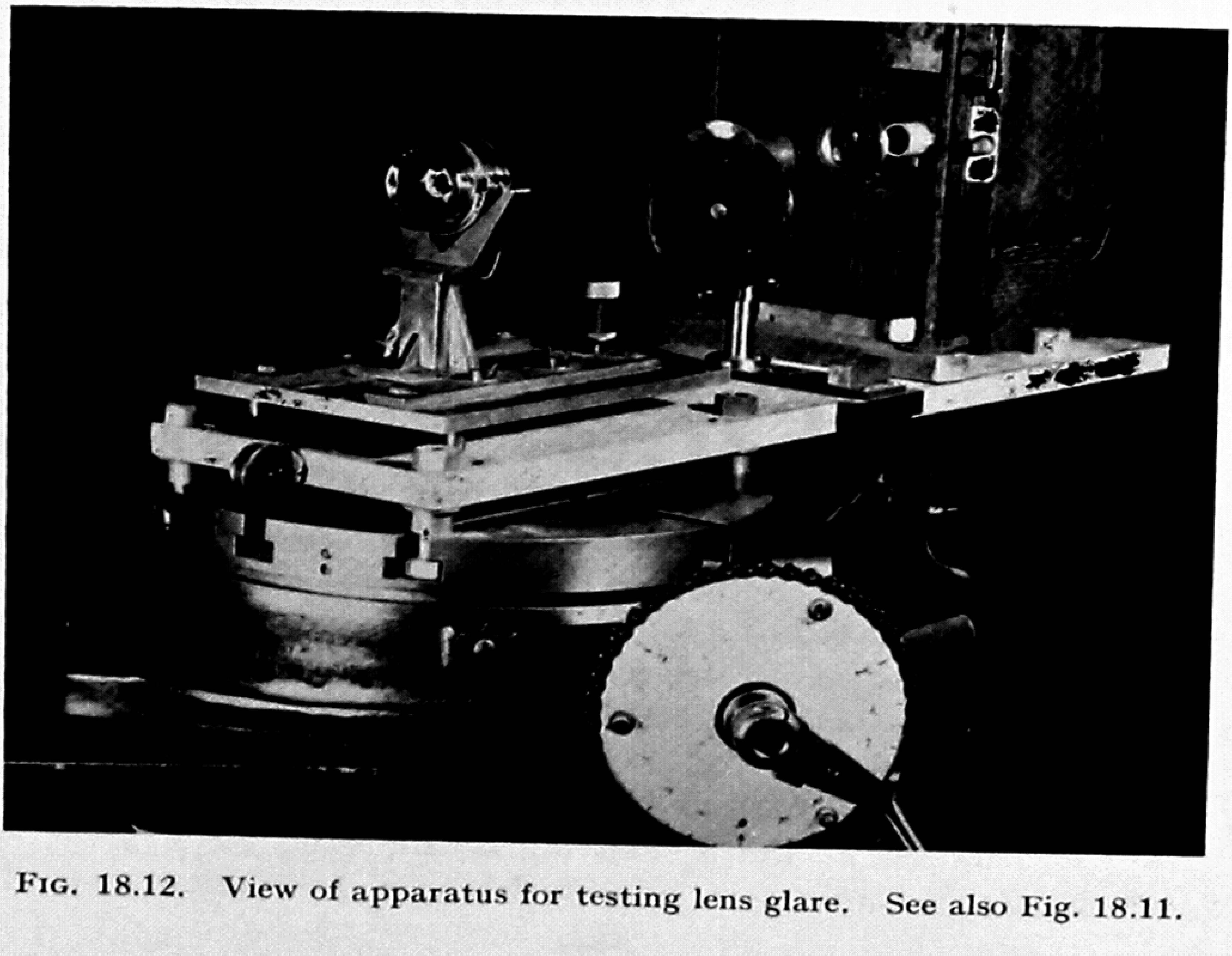

FIG. 18.12. View of apparatus for testing lens glare. See also Fig. 18.11.

It is between 0·50 and 0·55 for most sheets of the Ilford diffusing medium.

There are methods of obtaining the ratio of the veiling glare brightness to the illumination which do not depend on the relation of the brightness of a diffusing screen to its illumination, but these have no special advantages and are more difficult to perform than the method described.

Derivation of Glare Indices

From the curve relating β_θ to θ we can calculate the veiling glare at the centre of a circular uniform field of any angular radius either without a black disc at the centre, or with one of any diameter we choose, by integrating the effects at the centre of the field of all the elementary sources into which the field can be analysed.

All elementary areas in direction θ will form an annulus of angular radius θ and width $\delta\theta$, say, the origin of the angular co-ordinates being at the lens. The solid angle subtended by the annulus is $2\pi \sin \theta\delta\theta$. If B is the field brightness, the illumination from the annulus is $B \,.\, 2\pi \sin \theta\delta\theta$, and the equivalent background brightness of the veiling glare due to this illumination is $\beta \,.\, B \,.\, 2\pi \sin \theta\delta\theta$.

We may choose some convenient value for $\delta\theta$, say 1°. For this width $2\pi\delta\theta = 0{\cdot}1097$, or 0·11 as near as need be, and the brightness of the veiling glare is $0{\cdot}11\, \beta_\theta \,.\, B \,.\, \sin \theta$. We may write this as $G_\theta B$ where $G_\theta = 0{\cdot}11\beta_\theta \sin \theta$ and is the ratio to the field brightness of the veiling glare brightness due to an annulus one degree wide whose outer radius is $\theta + 0{\cdot}5$ degrees.

If we imagine the field divided up by circles of angular radii 1, 2, 3 . . . . 89, 90 degrees it then consists of a series of annular zones of mean radii ½, 1½, 2½ . . . . 88½, 89½ degrees. If we substitute these values in turn for θ, obtaining the appropriate value of β_θ from the graph derived from the point-source measurements, the resulting values of G_θ are the veiling glare brightnesses, per unit of objective field brightness, due to zones which, collectively, occupy the whole field from the centre to 90°.

If now we add the first n values of G_θ we obtain the total veiling glare brightness due to a circular field of radius n degrees. If we plot these totals against n we obtain a curve of which the ordinate at any angle is the veiling glare brightness at the centre of a field of that radius. It is convenient to refer to this as the zonal summation curve, and to denote its ordinate at n° by $\bar{g}_n$. If we subtract from the value for radius n degrees the value for a smaller radius n' we obtain the value of the veiling glare brightness at the centre when the central region of radius n' is dark, that is, in the circumstances which prevail when there is a black disc of this radius at the centre. If, as in the case of telescopes, we take as a standard for measurement purposes a black disc of 1 degree diameter, the total veiling glare brightness at the centre of the field, that, is the fictitious brightness of the disc, will be the difference between the ordinates of the zonal summation curve at n and at 0·5 degree, *i.e.* $\bar{g}_n-\bar{g}_{0\cdot5}$.

This gives the equivalent background brightness of the veiling glare as a fraction of the objective field brightness, but this is not the veiling glare index as this quantity has been defined, and as it is directly measured in the case of a telescope. The glare index for a field of radius n degrees with a central back disc of radius 0·5 degree is the ratio of the equivalent background brightness at the centre, when the disc is present, to the total brightness at the centre when the disc is removed. This latter quantity is equal to the objective field brightness plus the equivalent background brightness of the veiling glare due to the whole field, that is to $B(1+\bar{g}_n)$.

The conventional veiling glare index, g_n, for a field of n degrees radius is therefore

$$g_n=(\bar{g}_n-\bar{g}_{0\cdot5})/(1+\bar{g}_n) \tag{3}$$

It is sometimes convenient to use a single symbol, say $\mathbf{g}_n$, for the quantity $\bar{g}_n-\bar{g}_{0\cdot5}$. Then $\mathbf{g}_n=\mathbf{g}_n/(1+\mathbf{g}_n\, g_{0\cdot5})$. Even in a very dirty lens $g_{0\cdot5}$ is small compared with unity and can be neglected in the denominator without significant error, so we may write

$$g_n=\mathbf{g}_n/(1+\mathbf{g}_n). \tag{4}$$

This lead to the converse relation

$$\mathbf{g}_n=g_n/(1-g_n). \tag{5}$$

The equivalent background brightness, within the black spot, is $\mathbf{g}_n\, B$, or $\frac{g_n}{1-g_n}\, B$ where B is the true brightness of the surrounding field. This relation is useful in practical applications. But for the present we are concerned with the veiling glare index as an indication of the quality or condition of a lens. By plotting the values of g_n, obtained from (3), against n we can see the relative importance of the various zones of the field in degrading the contrast at the centre.

As an illustration of the kind of results obtained, Fig. 18.13 shows the values of g_n for fields of all radii up to 90° for a 20 inch f/6·3 aircraft camera lens of a well-known make. There is a rapid increase in the glare index with increase of field radius up to about 30°, after which the rate of increase is much less. 90% of the veiling glare due to a full 90° field is caused by the zones under 30°, and 98% of it by zones under 60°. The full value of g for this lens, which is typical of clean lenses of the particular pattern, is 2·95%.

A marked increase in veiling glare index, especially in the contribution of the inner zones of the field, is produced by dirt or film forming on the surfaces. Glare index forms a most sensitive test for cleanness.

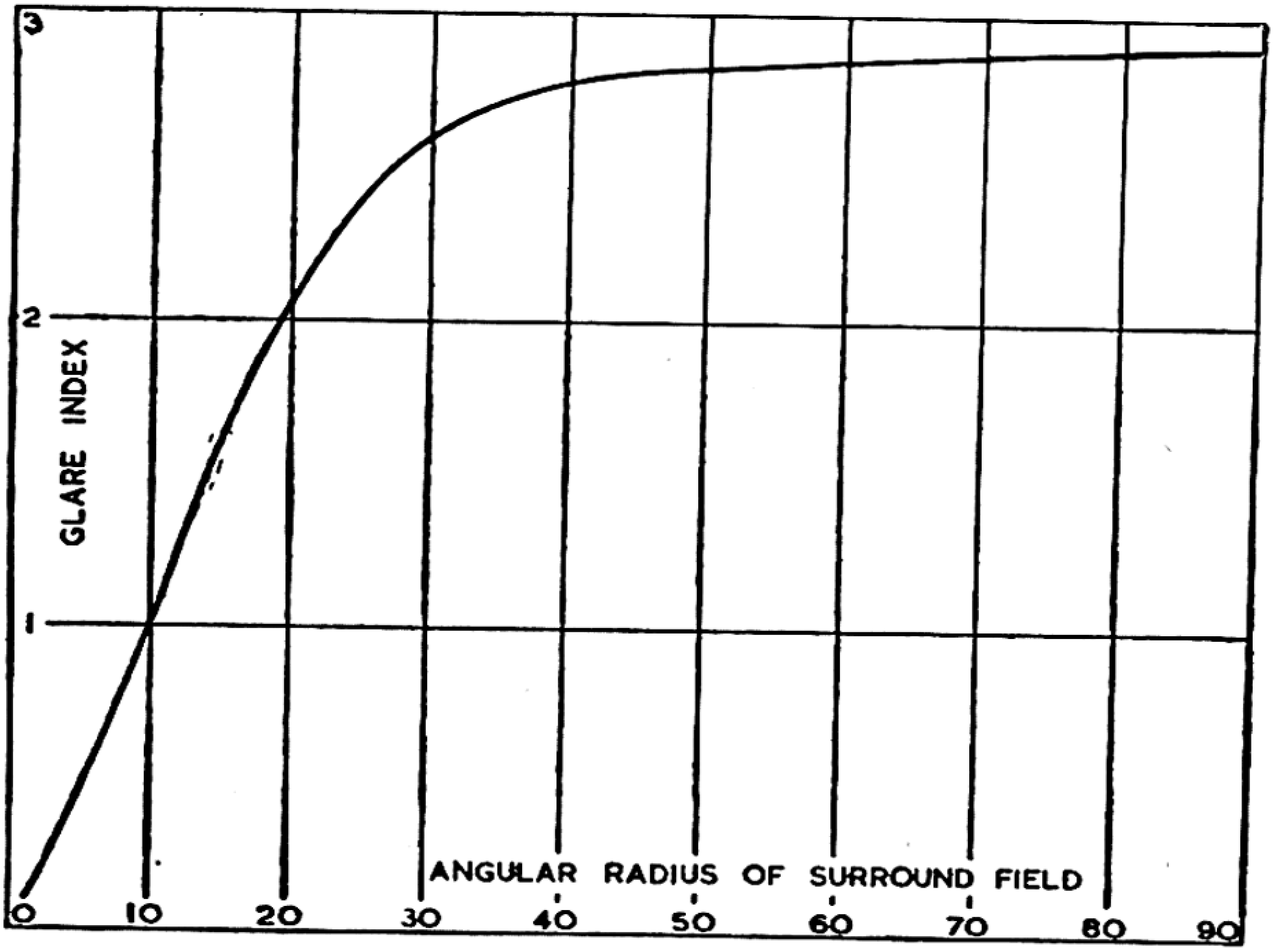

FIG. 18.13.

The foregoing method of determining veiling glare in lenses gives complete information about their properties, but it takes too much time both in observation and computation to be readily used either for routine testing or production control.

Unfortunately no accurate and convenient method for determining the veiling glare index of a photographic lens as quickly and easily as that employed for telescopes has so far been devised. For small lenses of short focus direct forms of test have been tried, some by myself and some by other workers, using the same basic method as for telescopes, but satisfactory approximation to prescribed conditions is difficult to attain.

An approximate method which employs a somewhat different principle, and which can be applied to lenses of any size within reason, is illustrated in Fig. 18.14.

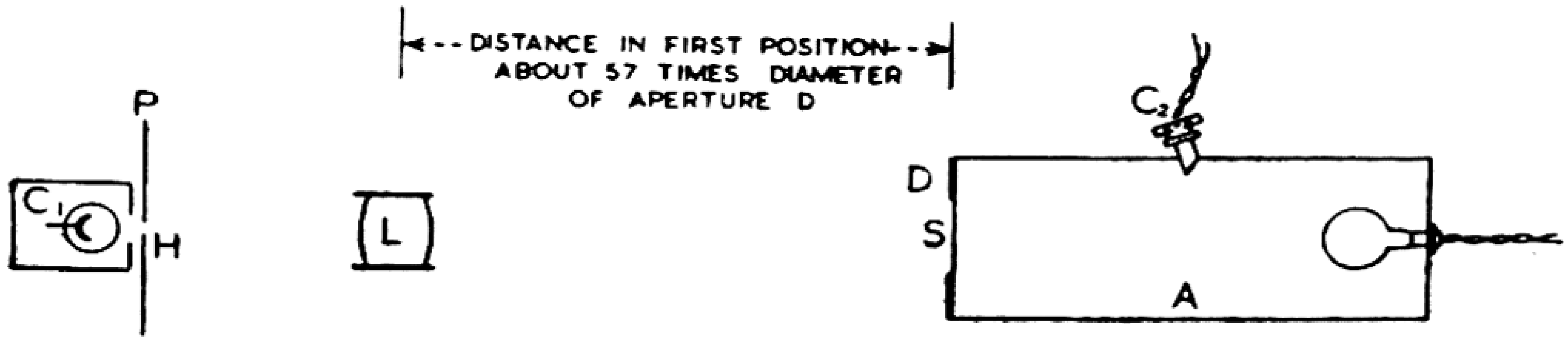
DISTANCE IN FIRST POSITION ABOUT 57 TIMES DIAMETER OF APERTURE D
P
C_1
H
L
C_2
D
S
A

FIG. 18.14.

L is the lens under test and *P* an opaque screen in the focal plane with an aperture *H* through which light passes to a photo-electric receiver, C_1. This aperture should subtend about 0·8 to 0·9 degrees at the back nodal point of the lens.

If the lens is not provided with a built-in shutter, an opaque disc, just sufficiently large to hide the whole of the lens from the hole *H*, should be mounted close to the lens on the side facing *H* to serve as a shutter.

A is a tubular lantern about 18 inches long and 7 inches diameter containing a 100 watt opal-bulb lamp. The tube is painted white inside and is closed at its front end with a sheet of Ilford diffusing medium *S*. In such a lantern the screen obeys Lambert's law very closely. Into the wall of the lantern is inserted a prismatic reflector by means of which a rectifier photo-cell, C_2, " sees " the inner side of the diffusing screen. Shields are fitted to ensure that no light from the lamp or walls of the tube can reach C_2, which can therefore be used to measure the interior brightness of the diffuser.

A small photographic shutter is built in between C_2 and the prism attachment to enable the zero reading of the cell to be checked before each measurement.

A diaphragm *D* of opaque black paper with a circular aperture of slightly greater diameter than the front component of the lens is attached to the screen *.

The test is carried out as follows : The lantern, which is mounted on a trolley, is taken to such a distance that the illuminated disc subtends one degree at the lens, and adjustment is made so that the circular patch of light formed in the focal plane is concentric with the aperture *H* which it will slightly overlap all round. The zero readings of the cells C_1 and C_2 are checked with the shutters closed. The shutters are then opened and the readings x_1 of cell C_1 and x_2 of cell C_2 are observed.

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* Some easily removed adhesive should be used, as a different diaphragm is required for each size of lens tested.

The combination of the lens L with the aperture H and photocell C_1 is, in effect, a brightness meter. If the lens were free from veiling glare the reading x_1 would measure, on the arbitrary scale of cell response, the brightness B of the diffusing screen, but when there is veiling glare the apparent brightness, as " seen " by the photocell through the aperture H and the lens, is increased by the equivalent background brightness of the veiling glare due to a field of 0·5 degree radius. That is,

$$x_1 = p[B(1+\bar{g}_{0\cdot5})], \tag{6}$$

where p is the scale factor relating responses of the lens-diaphragm-cell combination to brightness.

Both shutters are then closed* and the lantern moved forward until the surface of S is in contact with the rim of the lens mount. In this position it is equivalent to a complete hemispherical sky of practically uniform brightness. The shutters are opened and the cell readings x_1' and x_2' observed. The new reading x_1' now measures, on the same scale as before, the brightness of the screen plus the equivalent background brightness due to a complete hemispherical field, *i.e.*

$$x_1' = p[B'(1+\bar{g}_{90})], \tag{7}$$

where B' is the brightness of the screen in the second position. B' is always appreciably greater than B owing to light reflected back from the lens surfaces. In the distant position the screen receives a quite insignificant fraction of this light but in the close-up position it receives it all. Before we can derive information about veiling glare from (6) and (7) we must know the relation of B' to B. This we can obtain from the readings x_2 and x_2' of the cell C_2. These readings are proportional to the brightnesses of the inner surface of the screen but, as the light producing the change is incident on the side of the screen opposite to the one receiving the basic illumination, the two surfaces do not suffer the same fractional change in brightness.

The fractional changes are, however, in a constant ratio which we may denote by ρ, and $\frac{B'-B}{B} = \rho\frac{x_2'-x_2}{x_2}$, whence

$$B' = B\left(1+\rho\frac{x_2'-x_2}{x_2}.\right)$$

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* By keeping the shutters closed except when making observations, fatigue effects are reduced to a minimum.

Substituting this value of B' in (7) and combining with (6) we find that the veiling glare index of the lens for a full field of 90 degrees radius with a central black disc of 0·5 degree is (from equation 3)

$$g_{90} = \frac{\bar{g}_{90} - \bar{g}_{0\cdot 5}}{1 + \bar{g}_{90}} = 1 - \frac{x_1}{x_1'}\left(1 + \rho \frac{x_2' - x_2}{x_2}\right). \tag{8}$$

The factor ρ can easily be determined with the aid of a semi-reflecting plate. With the lantern in the distant position, the semi-reflecting plate is mounted close up to the screen. It produces a considerable increase in the brightness of the latter. The photocell C_1 in these circumstances will measure the increased brightness of the outer surface, reduced in proportion to the transmission factor of the semi-reflecting plate, and C_2 will measure the internal brightness. The semi-reflector is now moved back about a third or so of the distance towards the lens. Its effect in producing backward illumination on the screen is now greatly reduced and the screen brightness will fall. Readings of C_1 and C_2 are again taken. The two readings of C_2 give the fractional change in the brightness of the inside surface.

The effective transmission factor of the semi-reflecting plate is not altered by moving it, so the two readings of C_1 give the fractional change of the brightness of the outer surface and the value of ρ can be obtined.

Tests by this method can be carried through very quickly, especially of batches of lenses of one pattern for which the same field diaphragm D and the same positions of the lantern serve for all members of a batch. The drawback to the method for accurate work is the very obvious one that the required glare index is derived from the relatively small differences of several large quantities. To obtain a very moderate accuracy in the glare index requires that the cell responses be measured with high accuracy and that the lamp voltage be maintained with great precision.

The method may, nevertheless, be found useful where many lenses have to be tested and rapidity is more important than high accuracy.

The work described above has been carried out as part of the research programme of the National Physical Laboratory, and this paper is published by permission of the Director of the Laboratory.

SOMMAIRE

SUMMARY

On décrit un appareil construit au N.P.L. pour le mesure des propriétés photométriques fundamentales des systèmes afocaux et des objectifs photographiques. Il s'agit du facteur de transmission au centre du champ, de ses variations dans le champ, et de la perte de contraste causée par les diffusions et les réflexions multiples à l'interieur du système optique.

Pour obtenir un valeur numérique de la perte de contraste on mesure la brilliance de l'image d'un petit disque noir sur fond uniformement brilliant. La rapport de cette brilliance, dans des conditions précises de de diametre d'objet et position dans le champ, à la brilliance du champ a été appelé " Veiling Glare Index " de l'instrument . Il constitue une donnée numérique chraacterisant la perte de contraste dans les conditions normales.

The paper describes apparatus developed at the National Physical Laboratory for measuring the essential photometric properties of telescopes and photographic lenses. These properties are the paraxial transmission factor, the relative brightness of various zones of the field, and the degradation of contrast caused by scattering and multiple reflexion within the optical system.

To provide a numerical assessment of contrast degradation the brightness of the glare light within the image of a small circular black object at the centre of a uniformly bright object field is measured. The ratio of this brightness, under specified conditions of object diameter and field size, to the brightness of the field when the spot is removed has been termed the Veiling Glare Index of the instrument. It provides a convenient numerical criterion of contrast degradation under normal conditions of use.

DISCUSSION

MR. R. KINGSLAKE stated that his company estimated for camera lenses of the last type described by Mr. Guild directly by using a large internally whitened box, illuminated by screened lamps inside it. The lens was introduced into an aperture in one side and therefore received light from a complete hemisphere. Opposite the lens a small aperture acted as a black spot, which may be removed by closing the aperture with a white disk. The flare index varied from 100/1 to 10/1, the latter being regarded as unsatisfactory and the former as exceptionally good. In testing projectors, for which purpose a test object of opaque black bars and white spaces is satisfactory, it is important to distinguish between "micro-contrast" in which false light is thrown into small dark areas by aberrations and "macro-contrast" (the type dealt with by Mr. Guild) caused by more general diffusion of light. Making a small area really black is perhaps the greatest problem in testing projectors.

It was an interesting question whether a reduction in the general diffused light, for instance, by anti-reflection coastings, does not in fact increase the exposure required in taking a photograph. Certainly in those cases where the exposure is determined by the necessity to obtain detail in the shadows the reduction of intensity in the focal plane by reduction of flare would appear to make increased exposure necessary.

MR. J. GUILD replied that the difficulty with the arrangement used by Mr. Kingslake (and others) is that for long focus lenses an enormously large box or sphere is required. Attempts have been made to avoid this by employing a collimator or other optical device in conjunction with the box, but he believed that the method described was the better, particularly as it gave more information. The effect of anti-reflection coatings on the veiling glare was by no means as great as might be supposed. In the early days of anti-reflection coating there was very little reduction, and even now the veiling glare in coated camera lenses was at the best 40 per cent. of that in uncoated lenses. For binoculars the reduction in veiling glare was only 20 per cent.

MR. I. C. GARDNER stated that flare light had more than merely photometric effects, and, for example, could seriously influence measurements of resolving power.

DR. R. WOODSON asked if it were possible by Mr. Guild's measurements to distinguish between the effects of ghost images and general diffusion of light.

MR. J. GUILD replied that the intention of the measurements was to estimate the total flare light, from any causes whatever, and no attempt was made to distinguish in the way suggested by Mr. Woodson.

MR. R. E. REASON had found that extremely good approximation to a black spot could be obtained by using a blackened cone, facing forwards or backwards according to the circumstances of incidence of the light, in place of a black disc.

NEW OPTICAL MATERIALS

19. Synthetic Optical Crystals

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(Tufts College, U.S.A.)

THE use of optical elements made from crystalline materials is by no means new—the special characteristics of such familiar natural crystals as quartz, calcite, and fluorite have been employed by optical designers for many years. But the use of crystalline materials is now becoming much more wide-spread, probably due to two factors : first, the ready availability of artificially grown crystals ; and second, the increase of practical interest in the near infrared region of the spectrum, where optical glass does not transmit. There is also a growing industrial interest in the ultraviolet spectral region, due principally to the increasing use of ultraviolet spectrophotometry and to recent developments in ultraviolet microscopy.

The present report does not cover the more-or-less standard optical crystals such as quartz and calcite which still must be obtained from nature. Rather, it discusses the availability of the newer, artificially-produced crystals. With the single exception of fused silica, coverage of sources is restricted to the U.S.A. No attempt is made to list data on the optical and other physical properties of interest to optical and mechanical designers, since these data are to be found in the standard handbooks and regular literature sources. However, such data are sometimes included herein for the newest and/or the lesser-known crystals, whose properties may not yet be adequately described in the scientific literature.

The well-established prism materials for infrared spectrometers are sodium chloride, which can be used out to wavelengths of about 17 microns, and potassium bromide, which can be used to 30 microns. A new prism material which permits the extension of the useful range of prism instruments out to 40 microns is the mixed crystal thallium bromide-thallium iodide (42%–58%), which is often referred to by the German code name " KRS–5." Another new material which is being used extensively in infrared instrumentation is crystalline silver chloride, which transmits to about 25 microns. It is substantially insoluble in water, and hence is being used as a substitute for rock salt for absorption cell windows, etc. However, it is a much softer material, it is very corrosive, even to metals, and it darkens with exposure to actinic light unless suitably protected. Two important disadvantages of these new infrared materials, silver chloride and thallium bromide-iodide, are their softness, mechanical weakness and consequent susceptibility to cold flow ; and their high refractive indices of about 2·0 and 2·4 respectively, which result in very large reflection losses.

Crystal quartz has long been the favourite material for use in the ultraviolet, and it can be used down to the wavelength at which air ceases to transmit. Several other crystals, for example sodium chloride, potassium chloride, and potassium bromide, can be used to about 200 millimicrons. The use of these materials is usually avoided when possible, however, because of their high solubility in water. The most interesting of the ultraviolet-transmitting materials are calcium fluoride (fluorite) and lithium fluoride. When these are grown in vacuum from the molten salt, using carefully purified materials, they give ultraviolet transmission limits of around 125 and 105 millimicrons respectively. These two materials can be used through the visible region and into the near infrared, where their practical transmission limits for prisms are 6 microns for lithium fluoride and 9 microns for calcium fluoride. Another material which has been used a great deal in ultraviolet instrumentation is fused silica (also called fused quartz, vitreous silica, or quartz glass). Its ultraviolet transmission is almost as good as that of crystalline quartz, and of course it has the advantage of not being birefringent. However, its poor optical homogeneity has been a limiting factor for many applications. Fused silica of sufficiently high quality for use in microscope slides and other thin sections is available from several domestic sources such as the General Electric Company, the Hanovia Chemical and Manufacturing Company and the Thermal Syndicate. There is growing interest, however, in materials now available from the W. C. Heraeus Company of Hanau, Germany (near Frankfurt am Main) (Heraeus Quarzschmelze GMBH, Hanau). Their highest quality materials, called " Homosil " and " Ultrasil," appear to be quite satisfactory both from the point of view of homogeneity in long optical paths and as to good transmission to below 200 millimicrons. In view of the optical isotropy, the advantageous mechanical and chemical properties, and the very low thermal expansion of fused silica, these highly homogeneous varieties should enjoy increasing popularity in ultraviolet instrumentation.

Although the above comments have referred specifically to the infrared and ultraviolet, these several materials can of course be used also in the visible region. Such use is well-known in apochromatic microscope objectives and in other special combinations with the regular optical glasses where, for instance, better correction of secondary colour can often be obtained.

The principal producer of the optical crystals used for prisms and windows in infrared spectrometers and spectrophotometers is the Harshaw Chemical Company of 1945 East 97th Street, Cleveland 6, Ohio. They produce large synthetic optical-quality single crystals from the melt, following the methods developed by Bridgman and Stockbarger, whose patents are held by the Research Corporation of New York. Listed below are the materials which Harshaw is able to supply at the present time. The maximum-size optical element obtainable can be computed from the size of ingot which is grown, although in some cases it cannot be expected that the entire ingot will be comprised of a single crystal :

1. Sodium chloride, potassium chloride, and potassium bromide, grown in ingots 8 inches in diameter by approximately 6 inches high, topped by a 90° cone whose height is approximately 4 inches. These materials are readily available, but getting a single-crystal ingot of potassium bromide is still difficult, and rare.
2. Lithium fluoride, grown in vacuum, in ingots 6 inches in diameter by 4 inches high, topped by a 120° cone whose height is about 1½ inches. Readily available..
3. Calcium fluoride, grown in vacuum, in ingots 5 inches in diameter by approximately 3½ inches high, topped by a 120° cone whose height is approximately 1½ inches.
4. KRS–5 (thallium bromide-iodide), grown in ingots 3⅝ inches in diameter by approximately 3 inches high.
5. Silver chloride, grown in ingots approximately 3¼ inches in diameter by 4 inches long, and weighing approximately 10 pounds. Pieces can be cut from an ingot, for prism blanks, etc., or the material can be rolled into sheets of any thickness down to 0·25mm. The sheets can be furnished either clear or coated with silver sulfide

for protection against actinic radiation. Since the steel rolls are 20 inches wide, the weight of the ingot and the thickness of sheet desired determine the maximum length sheet which can be supplied.

In addition to the above, Harshaw grows a number of crystals for use in scintillation counters. The information on these crystals is given here since some of them are also of interest optically—particularly the potassium iodide and the sodium iodide.

6. Potassium iodide, pure or activated with thallium, grown in ingots 8 inches in diameter by 6 inches high.

7. Sodium iodide, pure or activated with thallium, grown in ingots 8 inches in diameter by 6 inches high.

8. Naphthalene, grown in ingots approximately 18 inches in diameter by 6 inches high, containing multiple crystals but with clear sections several inches across.

9. Anthracene, grown in ingots approximately 3⅝ inches in diameter by 3 to 4 inches high. The ingots are multiple-crystalline, but random pieces broken or cleaved from the mass and weighing up to 20 or 30 grams each are available.

Another manufacturer of synthetic optical single crystals using the Bridgman and Stockbarger method is the Optovac Company, 112 Bickford Street, Boston 30, Massachusetts. The only foreign agent for the Optovac Company is Mr. Dan E. Mayers, 214 East 18th Street, New York 3, New York. At the present time this company is able to supply lithium fluoride and calcium fluoride. These are of course grown in vacuum, so as to have the best ultraviolet transmission. The sizes available can be judged from the following information :

1. Lithium fluoride, grown in vacuum, in ingots 4¾ inches in diameter by 4 inches high, topped by a 120° cone.

2. Calcium fluoride, grown in vacuum, in ingots 4 inches in diameter by about 3½ inches high, topped by a 120° cone.

Optovac is also growing some sodium chloride, in the size specified above for lithium fluoride. This company is also experimenting with barium fluoride, which is similar to calcium fluoride in being a cubic crystal with octohedral cleavage. Its ultraviolet transmission is very good, extending well below 200 millimicrons, and it transmits into the infrared to about 13 microns, which makes it of interest as a possible substitute for the much more water-soluble sodium chloride. Its refractive index in the visible is about 1·46 and its reciprocal dispersion is about 105. It lies between lithium fluoride and calcium fluoride in water solubility.

Another company which is just undertaking the growing of synthetic crystals is Pilot Chemicals, Inc., 47 Felton Street, Waltham 54, Massachusetts. They now grow potassium bromide, and expect to be able to furnish other alkali halides in the near future.

Perhaps mention should be made here of other laboratories where optical crystals have been produced in the past or are currently being produced, but whose products are not generally available on a commercial basis. At the Engineer Research and Development Laboratories of the Corps of Engineers, U.S. Army, Fort Belvoir, Virginia, there has been produced a relatively large amount of KRS-5 (thallium bromide-iodide), and also the related mixed crystal, thallium bromide-chloride (KRS–6). Crystals of the single salts of thallium and of certain lead halides have been produced here, and also in the Crystal Section of the Naval Research Laboratory, Washington 20, D.C., where a number of other crystals have been grown in small sizes, on an experimental basis. Small quantities of a large number of different crystals have been grown at the National Bureau of Standards, Washington 25, D.C. In general, however, crystals grown in these various government laboratories can be obtained only by government workers or U.S. workers who are involved in government research and development projects. Professor D. C. Stockbarger of the Massachusetts Institute of Technology has produced the optical crystalline fluorides of lithium, calcium, strontium, and barium in experimental lots. Oriented plates (basal sections) of sodium nitrate two to four inches in diameter by about ½ inch thick were grown by the Polaroid Corporation of Cambridge 39, Massachusetts, in 1943–1945, but this material is no longer in production at Polaroid.

In addition to the well-known alkali halides and other cubic crystals which have the very desirable characteristic of optical isotropy, there are some crystalline materials which, while not produced primarily for optical purposes, still find applications in optical instrumentation. These will hence be discussed briefly. The Linde Air Products Company, East Park Drive and Woodward Avenue, Tonawanda, New York, produces synthetic sapphire, ruby, spinel and rutile. Water-white synthetic crystals of sapphire or corundum ($Al_2 0_3$), of spinel ($Mg0 \cdot 3.5Al_2 0_3$), and also of rutile ($Ti0_2$), are available for optical use. The first two named have a transmission region extending from about 200 millimicrons to 6 microns, while rutile is transparent from the blue to almost 6 microns. The outstanding property of these materials is of course their extreme surface hardness and abrasion resistance, and their high melting point of around 2000°C. They also exhibit zero water absorption and extremely high chemical resistance. From the point of view of optical instrumentation they are of special interest because they retain their mechanical strength up to very high temperatures. This suggests their use as windows in furnaces, envelopes for high-pressure discharge lamps, etc. Sapphire is a hexagonal crystal, spinel is cubic, and rutile is tetragonal. Their refractive indices are high, those of sapphire and spinel being over 1·7 and those of rutile being 2·6 and 2·9. These materials are available in only rather small sizes, as follows : sapphire, in boules which are roughly cylindrical in shape, of diameters up to 1 inch and lengths up to 2½ inches ; spinel, in cylinders of diameters up to ¾ inch and lengths up to 2 inches. These materials are also available in the form of rods a fraction of an inch in diameter and up to several inches in length. The available sizes of rutile are not specified since the production of this crystal is still in a somewhat experimental state.

The Brush Development Company, 3405 Perkins Avenue, Cleveland 14, Ohio, is a leading producer of piezoelectric materials, and has been supplying Rochelle salt for many years. Most of its crystals are grown from water solution. A relatively new piezoelectric material which is of optical interest is " ADP " (ammonium dihydrogen phosphate : $NH_4{\cdot}H_2PO_4$). Blanks of this uniaxial crystal are available in unlimited quantities, in sizes up to 2½ inches in any specified directions. Plates up to 5 inches by 5 inches can be cut perpendicular to the optic axis. This crystal is stable to 140°C. Its ordinary and extraordinary refractive indices for sodium light are 1·5242 and 1·4787, respectively ; its transmission region extends from below 200 millimicrons to about 1·5 microns. The electro-optical properties of this material are of special interest in certain applications. The Brush Development Company can also supply pilot-plant quantities, in sizes up to 1 inch in any direction, of " KDP " (potassium dihydrogen phosphate). This material is stable up to 170° C ; its refractive indices are 1·5095 and 1·4684. Other materials manufactured by Brush include sodium chlorate, which is optically active ; potassium alum, a cubic crystal of low dispersion ; sodium nitrate, with refractive indices 1·5874 and 1·3361 (note the very large birefringence) ; and of course Rochelle salt, which is biaxial.

Finally, crystalline magnesium oxide (beta-magnesia or periclase) is available from the Norton Company of Worcester, Massachusetts and Niagara Falls, Ontario, Canada. This material is produced primarily as a refractory, but small crystals of optical quality are sometimes available on a by-product basis. The transmission range of selected crystals of this material is 220 millimicrons to 7 microns. With its refractive index for sodium light of 1·74 and its reciprocal dispersion of 53·5, it should be useful in achromatic lenses or prisms, perhaps combined with quartz. Its high melting point of 2800° C and its good resistance to acids, metallic vapours, etc., suggest its use for windows in high-temperature furnaces.

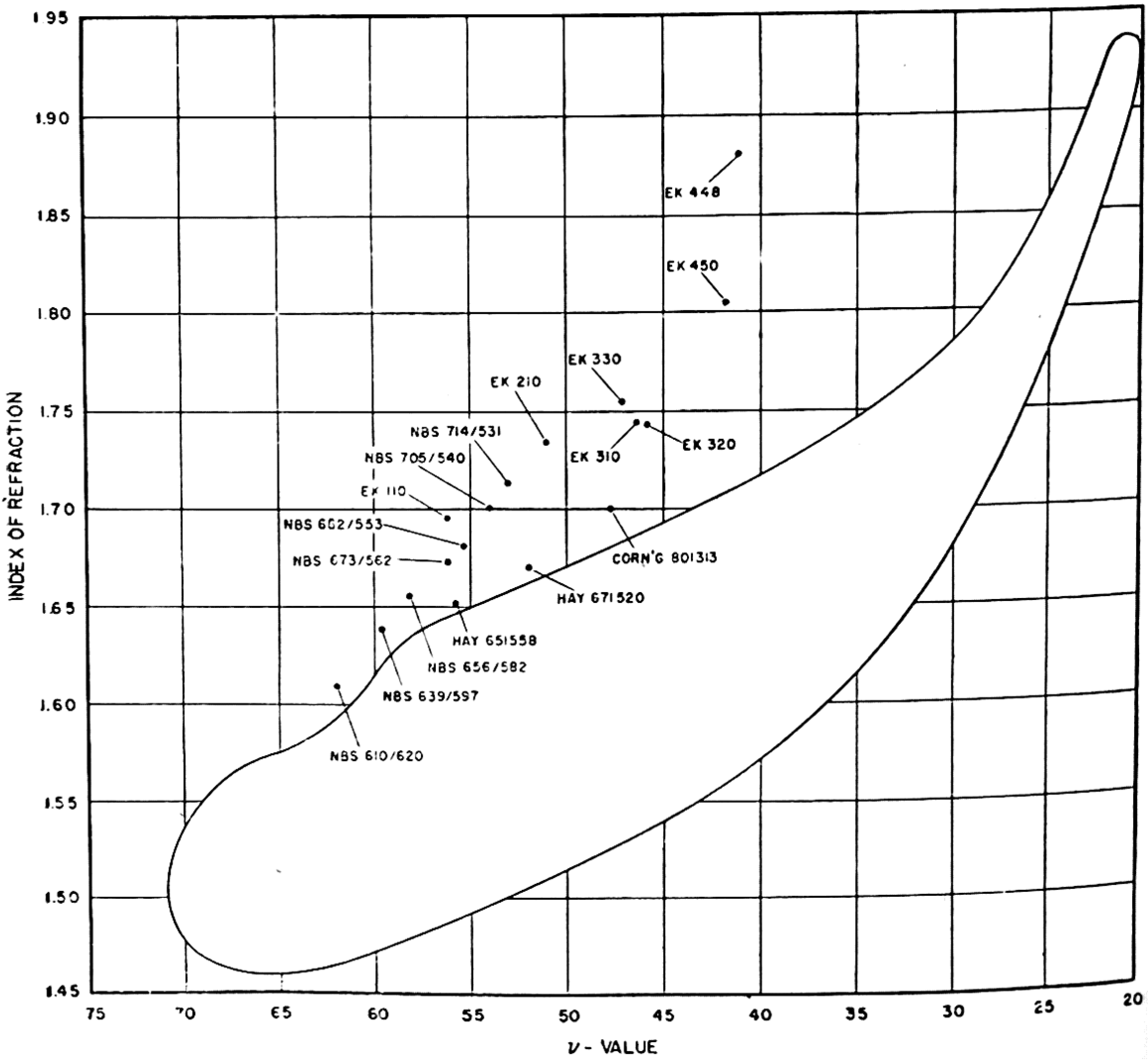

FIG. 20.1. Characteristics of new glasses (U.S.A.).

20. New types of Optical Glasses available in the United States

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National Bureau of Standards, U.S.A.

Optical glasses are regularly produced in the United States by :

Bausch & Lomb Optical Company, Rochester, New York.
Corning Glass Works, Corning, New York.
Eastman Kodak Company, Rochester, New York.
Hayward Scientific Glass Corporation, Whittier, California.
Pittsburgh Plate Glass Company, Pittsburgh, Pennsylvania.

and, chiefly on an experimental basis, by the National Bureau of Standards. The " classical glasses," available prior to 1935, are listed in the catalogues published by these firms and available on request. In addition to these glasses, within the past 15 years new glasses have been introduced and made commercially available with optical constants significantly different from the earlier listed glasses.

In order that the importance of these new glasses may be readily appraised their characteristic constants have been shown on Fig. 20.1. For this figure, following the usual practice, the values of

$$\nu = \frac{N_D - 1}{N_F - N_C}$$

have been plotted as abscissae and the indices of refraction as ordinates. The larger clear area without coordinate lines represents the portion of the area occupied by optical constants of the glasses that have been available for the past 30 or 40 years or longer. This area was determined by reference to a single catalogue which presents a very great variety of optical glasses. The new glasses, of which there are 17 different types, are plotted with the type designations as applied by the manufacturer. On this plot, the manufacturers are referred to as follows :

Corn'g	Corning Glass Works.
EK	Eastman Kodak Company.
Hay	Hayward Scientific Glass Corp.
NBS	National Bureau of Standards.

Tabulated values of the constants of these glasses, as furnished by the manufacturers, follow :

Origin	Type			Indices of Refraction			
		μ	A'	C	D	F	G'
NBS	610/620	62·0		1·6067	1·6096	1·6165	1·6220
NBS	639/597	59·7		1·6363	1·6395	1·6470	1·6531
NBS	656/582	58·2		1·6522	1·6555	1·6634	1·6698
EK	EK–110	56·2	1·68877	1·69313	1·69680	1·70554	1·71255
NBS	673/562	56·2		1·6697	1·6733	1·6817	1·6885
Hay	651/558	55·8		1·64757	1·65100	1·65924	1·66590
NBS	682/553	55·3		1·6782	1·6819	1·6906	1·6976
NBS	705/540	54·0		1·7011	1·7049	1·7142	1·7216
NBS	714/531	53·1		1·7103	1·7143	1·7238	1·7315
Hay	671/520	52·0		1·66724	1·67100	1·68018	1·68772
EK	EK–210	51·2	1·72482	1·72979	1·73400	1·74413	1·75235
Corn'g	8313	47·8		1·69639	1·70065	1·71104	
EK	EK–330	47·2	1·74499	1·75043	1·75510	1·76643	1·77571
EK	EK–310	46·4	1·73491	1·74033	1·74500	1·75638	1·76577
EK	EK–320	45·8	1·73432	1·73978	1·74450	1·75603	1·76557
EK	EK–450	41·8	1·79180	1·79814	1·80370	1·81738	1·82880
EK	EK–448	41·1	1·86714	1·87420	1·88040	1·89564	1·90827

Reference to additional glasses, of which the detailed optical constants have not been published, will be found in the article " New Optical Glasses," by R. Kingslake and P. F. de Paoles, *Scientific Monthly*, **68**, 420 (1949).

The addition of these new glasses provides the optical designer with means for better satisfying the Petzval condition governing the curvature of field and can result in less strongly curved surfaces for systems of a given focal length, thereby permitting better correction of zonal spherical aberration.

21. Plastic Glasses

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Among the very great number of organic plastics which have been made industrially and in the laboratory there are some which are comparatively hard, clear solids having a superficial similarity to glass. These have understandably attracted the attention of the optical physicist ; some interesting early developments making use of the transparency placed less exacting demands on the materials. Examples are the use of cellulose acetate and to a greater extent polymethyl methacrylate sheet for the glazing of aircraft. The optical properties of these materials are quite adequate for this application and it is the fact that they can be shaped readily by simple techniques which makes them particularly suitable. Another use which does not demand great accuracy is the making of protective goggles, and here again considerable effort has been expended.

The problem of reaching a reasonably high standard of accuracy in plastic optical components was not considered very seriously before 1939, although attention was drawn by Morgan *et al*[1], Yarsley[2] and by Moore[3] to the possibilities which existed for transparent plastic materials.

At a Physical Society Symposium on " Recent Optical Materials " in 1942 Wearmouth[4] presented a general survey of the main transparent plastics then available. He discussed the cellulose derivatives, urea and formaldehyde resins and a variety of polymerisation products including polyvinyl acetate, polyvinyl chloride, polymethyl isopropenyl ketone, polystyrenes and polyacrylates. Of these, the only materials which showed much promise were in the last three classes. The paper brings out the point that the available range of optical properties should permit the manufacture of achromatic doublets.

The danger which arose in 1940 of acute shortages of optical glass had stimulated interest in plastics as possible substitutes and programmes of work were started, both in the United States and Great Britain, with the aim of improving existing materials, finding new polymers and of developing manufacturing techniques which would enable a high degree of accuracy to be attained.

A report[5] has recently been made generally available : this covers the work done by the Polaroid Corporation under the aegis of the National Defense Research Committee and is probably the most comprehensive review of the subject. Over 100 polymers were examined in detail and it is concluded that for accurate components polystyrene and polycyclohexyl methacrylate are the most suitable materials. Polymethyl methacrylate is suitable for all but the most exacting applications. Polyvinyl isopropenyl ketone is not viewed with favour.

General Properties

Because of certain common essentials of structure all plastic materials show some marked similarities in properties. The molecules are built up from comparatively simple units joined end to end so that in the simplest case they consist of a long carbon-carbon chain carying two substituent atoms or radicles on each carbon atom : and example is polystyrene, a linear polymer.

The molecules are very long and may contain many thousands of carbon atoms in the main chain.

Some of the known plastics are naturally occuring high polymers whilst others are derived from them by chemical modification of the side groups. A third class of increasing importance is that which is obtained by polymerisation of simple reactive molecules (monomers) into long chain structures. The monomers are for the most part liquid which under the influence of a catalyst and heat and light, react to a form a solid polymer.

Because of the flexibility of the molecules and of the fact that in the mass they are held together in all amorphous polymers by van der Waals forces, the influence of temperature changes is profound. Increase in temperature leads to a softening of the material and those plastics which are hard and rigid at room temperature take on the properties of viscous liquids or rubbery solids if they are suitably heated. Above the softening range, which may be between 80° and 150° C for linear polymers they can be moulded to any desired shape which can then be retained at lower temperatures.

Not all polymers conform to this simple long chain structure: the chains may be branched or even joined together into a three-dimensional network, in which case they are known as cross-linked polymers. The distinction between these and linear polymers is important for they are no longer easily deformed under the influence of heat, and in addition are harder and approximate more closely to glass in their physical properties. They have not, however, been widely used because the existing fabrication methods are such that considerable internal strain is generally introduced.

The interrelation of the structure of polymers with their properties has been the subject of much published research and some excellent summaries are available[6]. In addition there are detailed works which enumerate the actual values of mechanical, thermal, and general physical properties[7]. A short comparison of the physical properties of glass and of rigid plastics may not, however, be out of place here. A more detailed account will be found in Ref. 3.

All transparent plastics are much less dense than glasses, the specific gravity at 20° C having values between 1·0 and 1·5. This factor is immaterial for most applications but may assume importance in some instruments.

The thermal softening of linear polymers has already been discussed. An associated effect is the thermal expansion which is high, being about ten times that of glasses. This has serious, but not insuperable, repercussions upon the problem of mounting plastic components.

Mechanically, plastics are more easily deformable and softer than glasses. An average figure for Young's modulus of the materials now in use is $2-10 \times 10^5$ lb sq./inch. With this is associated, however, a rather high resistance to impact.

A property of plastics, which is of great importance, is their behaviour towards various chemical reagents. No generalisations can be made as their specific reactions are a function of the chemical nature of the polymer molecule. All glass-like polymers are, without exception, attacked by some reagents. The reagent may swell the plastic or it may dissolve it completely. These effects may not be serious, as precautions can, for the most part, be taken to avoid contact with harmful solvents. Water vapour is an exception as it is virtually unavoidable and is absorbed by a great number of polymers which consequently show a change, not only of refractive index, but of surface contour, upon exposure to humid conditions.

The important general physical properties of polystyrene and polycyclohexyl methacrylate at present being used for optical purposes are given in Table I; polymethyl methacrylate, which is also used in the optical field, has similar properties.

TABLE 1

	Polystyrene	Polycyclohexyl Methacrylate
Specific Gravity	1·049	1·095
Water Absorption (percentage increase weight of desiccated sheets 1 mm. thick on soaking in water at 20° C. until saturated)	0,1%	0,3%
Softening Point (Vicat)	100	105
Tensile Strength (lbs./sq. inch)	2,000	1,250
Impact Strength (notched Izod) (ft./lbs. per inch of notch)	·24	·14
Coefficient of Linear Expansion (per degree C.)	7·1 × 10-5	7·6 × 10-5
Hardness (modified Rockwell test with 20 Kg. major and 10 Kg. minor load. Reference 5)	103–105	107–109
	(Both lie between 2 and 3 on Moh's scale.)	
Thermal Conductivity (c.g.s. units) ...	2·2 × 10-4	2·3 × 10-4

Optical Properties

Homogeneity and transparency are prime requirements for plastics which are to be used for optical purposes. Homogeneity is largely achieved by careful control of the purity of the monomer, of the polymerisation reaction, and by care in any subsequent operations[5]. The reproducibility from batch to batch is also quite good: an accuracy ± 0·0001 in the refractive index has been claimed[8], although more recent work[5] suggests that in normal manufacturing operations ± 0·001 would be a more readily obtained standard. Among the better plastics transparency compares well with glass and there is a tendency for more of the spectral range to be covered than by most glasses. Rice *et alii*[9] have examined 17 compounds, and other workers have made more detailed examinations in certain parts of the spectrum[10].

The refractive index and dispersion of a number of polymers have been measured [5, 11] and the possibility of making achromatic combinations has been pointed out. The plot of refractive index *vs.* dispersive power which is shown in Fig. 21.1 is compiled from all available information and brings out a significant fact. Although well over a hundred compounds of very diverse constitution have been examined they all lie within a comparatively narrow band and there are no organic glasses which correspond in optical properties to the dense barium crowns and extra dense flints. This is a very serious shortcoming from the point of view of the designer. Furthermore, theoretical considerations indicate that there may be fundamental difficulties in obtaining plastics with properties in these ranges.

The refractive indices of polystyrene and polycyclohexyl methacrylate have been measured[5] and average figures are given below.

Polystyrene

Spectral Line	Wavelength A	Refractive Index at 15° C.	35° C.	55° C.
A	7679	$1{\cdot}581^{2}$	$1{\cdot}578^{5}$	$1{\cdot}575^{8}$
C	6563	$1{\cdot}587^{0}$	$1{\cdot}584^{3}$	$1{\cdot}581^{6}$
D_1	5896	$1{\cdot}592^{3}$	$1{\cdot}589^{7}$	$1{\cdot}586^{9}$
F	4861	$1{\cdot}606^{2}$	$1{\cdot}603^{4}$	$1{\cdot}600^{6}$
g	4358	$1{\cdot}617^{6}$	$1{\cdot}614^{8}$	$1{\cdot}612^{0}$

Polycyclohexyl Methacrylate

Spectral Line	Wavelength A	Refractive Index at 15° C.	35° C.	55° C.
A	7679	$1{\cdot}501^{6}$	$1{\cdot}499^{2}$	$1{\cdot}496^{4}$
C	6563	$1{\cdot}504^{4}$	$1{\cdot}502^{1}$	$1{\cdot}499^{2}$
D_1	5896	$1{\cdot}507^{1}$	$1{\cdot}504^{6}$	$1{\cdot}501^{8}$
F	4861	$1{\cdot}513^{4}$	$1{\cdot}501^{0}$	$1{\cdot}508^{1}$
g	4358	$1{\cdot}518^{4}$	$1{\cdot}516^{0}$	$1{\cdot}513^{1}$

Similar figures for polymethyl methacrylate are available from another source[12] for specimens which have been stored in normal room conditions for six months. The measurements were made at 20° C.

Spectral Line	Wavelength A	Refractive Index at 20° C.
C	6563	$1{\cdot}489^{0}$
D	5896	$1{\cdot}491^{3}$
e	5461	$1{\cdot}493^{3}$
F	4861	$1{\cdot}497^{5}$
g	4358	$1{\cdot}501^{9}$

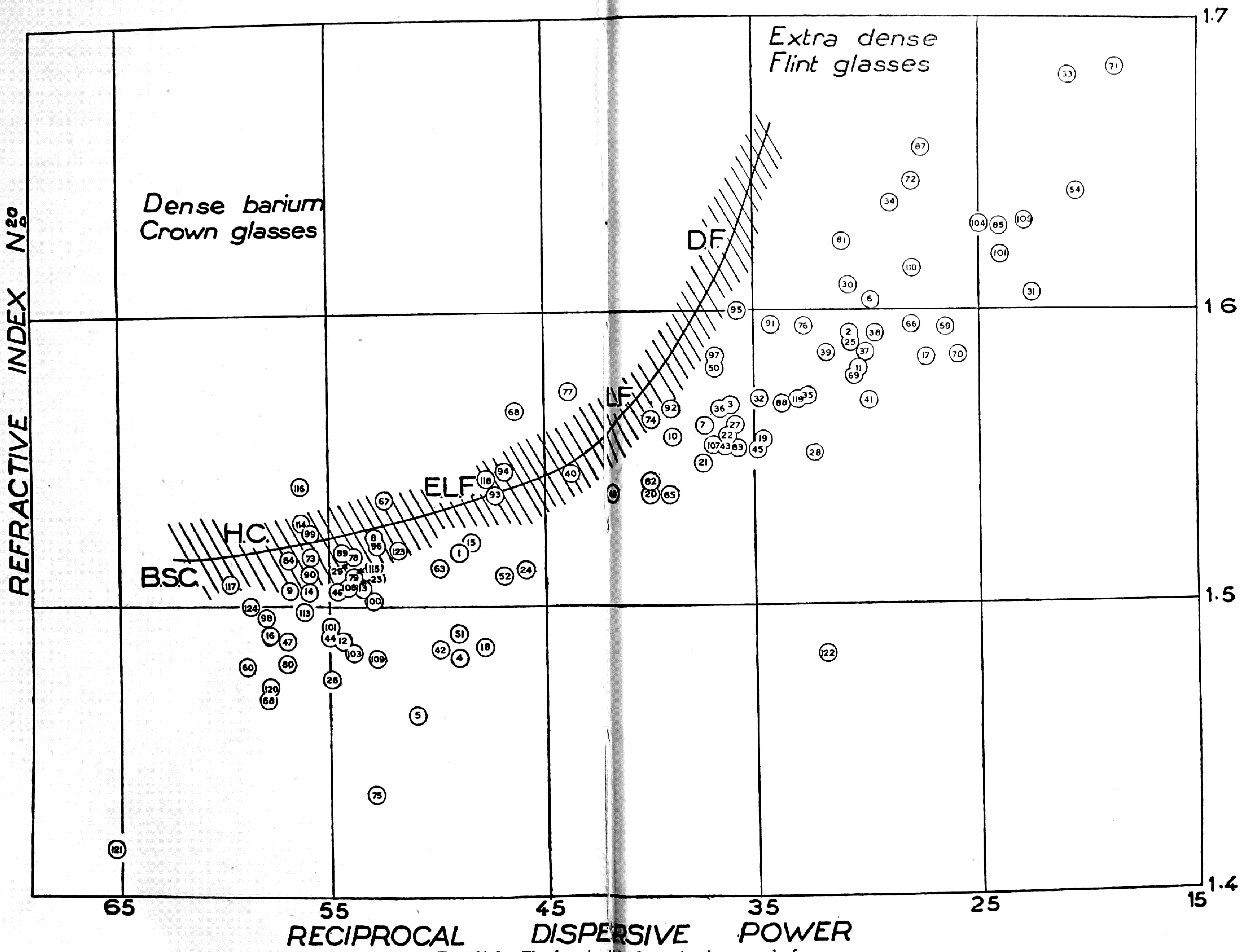

FIG. 21.2. The key to this figure is given overleaf.

KEY TO FIGURE 21.1

No. on Graph	Name of Monomer	Optical Properties of Polymer	
		Refractive Index (N^{20})	Reciprocal dispersive Power
1	Allyl methacrylate	1·5196	49·0
2	Benzhydryl methacrylate	1·5933	31·0
3	Benzyl methacrylate	1·5680	36·5
4	*n*-butyl methacrylate	1·483	49
5	Tert-butyl methacrylate	1·4638	51
6	*o*-chlorobenzhydryl methacrylate	1·6040	30
7	α-(*o*-chlorophenyl)-ethyl methacrylate	1·5624	37·5
8	Cyclohexyl-cyclohexyl methacrylate	1·5250	53
9	Cyclohexyl methacrylate	1·5064	56·9
10	*p*-cyclohexyl-phenyl methacrylate	1·5575	39·0
11	α-β-diphenyl-ethyl methacrylate	1·5816	30·5
12	Menthyl methacrylate	1·4890	54·5
13	Ethylene dimethacrylate	1·5063	53·4
14	Hexamethylene glycol dimethacrylate	1·5066	56
15	Methacrylic anhydride	1·5228	48·5
16	Methyl methacrylate	1·4913	57·8
17	*m*-nitro-benzyl methacrylate	1·5845	27·4
18	2-nitro-2-methyl-propyl methacrylate	1·4868	48
19	α-phenyl-allyl methacrylate	1·5573	34·8
20	α-phenyl-*n*-amyl methacrylate	1·5396	40
21	α-phenyl-ethyl methacrylate	1·5487	37·5
22	β-phenyl-ethyl methacrylate	1·5592	36·5
23	Tetrahydrofurfuryl methacrylate	1·5096	54
24	Vinyl methacrylate	1·5129	46
25	Styrene	1·5907	30·8
26	Vinyl formate	1·4757	55
27	Phenyl cellosolve methacrylate	1·5624	36·2
28	*p*-methoxy-benzyl methacrylate	1·552	32·5
29	Ethylene chlorohydrin methacrylate	1·517	54
30	*o*-chlorostyrene	1·6098	31
31	Pentachlorophenyl methacrylate	1·608	22·5
32	Phenyl methacrylate	1·5706	35·0
33	Vinyl naphtalene	1·6818	20·9
34	Vinyl thiophene	1·6376	29
35	Eugenol methacrylate	1·5714	33
36	*m*-cresyl methacrylate	1·5683	36·8
37	*o*-methyl-*p*-methoxy styrene	1·5868	30·3
38	*o*-methoxy styrene	1·5932	29·7
39	*o*-methyl styrene	1·5874	32
40	Ethyl sulphide dimethacrylate	1·547	44
41	Allyl cinnamate	1·57	30
42	Diacetin methacrylate	1·4855	50
43	Ethylene glycol benzoate methacrylate	1·555	36·8
44	Ethyl glycolate methacrylate	1·4903	55
45	*p*-isopropyl styrene	1·554	35
46	Bornyl methacrylate	1·5059	54·6
47	Triethyl carbinyl methacrylate	1·4889	57
48	Butyl mercaptyl methacrylate	1·5390	41·8
50	*o*-chlorobenzyl methacrylate	1·5823	37
51	α-methallyl methacrylate	1·4917	49
52	β-methallyl methacrylate	1·5110	47
54	α-naphthyl methacrylate	1·6411	20·5
58	Ethyl acrylate	1·4685	58
59	Cinnamyl methacrylate	1·5951	26·5
60	Methyl acrylate	1·4793	59
63	Terpineyl methacrylate	1·514	50
65	Furfuryl methacrylate	1·5381	39·2

No. on Graph	Name of Monomer	Optical Properties of Polymer	
		Refractive Index (N^{20})	Reciprocal dispersive Power
66	*p*-methoxy styrene	1·5967	28
67	β-amino-ethyl methacrylate	1·537	52·5
68	Methyl α-bromoacrylate	1·5672	46·5
69	Vinyl benzoate	1·5775	30·7
70	Phenyl vinyl ketone	1·586	26·0
71	Vinyl carbazole	1·683	18·8
72	Lead methacrylate	1·645	28
72	2-chlorocyclohexyl methacrylate	1·5179	56
74	1-phenyl-cyclohexyl methacrylate	1·5645	40
75	Triethoxy-silicol methacrylate	1·436	53
76	*p*-bromophenyl methacrylate	1·5964	33
77	2-3 dibromopropyl methacrylate	1·5739	44
78	Diethyl-amino-ethyl methacrylate	1·5174	54
79	1-methyl-cyclohexyl methacrylate	1·5111	54
80	*n*-hexyl methacrylate	1·4813	57
81	2-6-dichlorostyrene	1·6248	31·3
82	β-bromo-ethyl metacrylate	1·5426	40
83	μ-polychloroprene	1·5540	36
84	Methyl α-chloracrylate	1·5172	57
85	β-naphthyl methacrylate	1·6298	24
87	Vinyl phenyl sulphide	1·6568	27·5
88	Methacryl methyl salicylate	1·5707	34
89	Methyl isopropenyl ketone	1·5200	54·5
90	Ethylene glycol mono-methacrylate	1·5119	56
91	N-benzyl methacrylamide	1·5965	34·5
92	β-phenyl-sulphone ethyl methacrylate	1·5682	39
93	N-methyl methacrylamide	1·5398	47·5
94	N-allyl methacrylamide	1·5476	47
95	Methacryl-phenyl salicylate	1·6006	36
96	N-β-methoxyethyl methacrylamide	1·5246	53
97	N-β-phenylethyl methacrylamide	1·5857	37
98	Cyclohexyl α-ethoxyacrylate	1·4969	58
99	1-3-dichloropropyl-2-methacrylate	1·5270	56
100	2-methyl-cyclohexyl methacrylate	1·5028	53
101	3-methyl-cyclohexyl methacrylate	1·4947	55
103	3-3-5-trimethyl-cyclohexyl methacrylate	1·485	54
104	N-vinyl phthalimide	1·6200	24·1
105	Fluorenyl Mothacrylate	1·6319	23·1
106	α-naphthyl-carbinyl methacrylate	1·63	25
107	*p*-*p*^{3}-xylylenyl dimethacrylate	1·5559	37
108	Cyclohexanediol-1-4 dimethacrylate	1·5067	54·3
109	Ethylidene dimethacrylate	1·4831	52·9
110	*p*-divinyl benzene	1·6150	28·1
113	Decamethylene glycol dimethacrylate	1·4990	56·3
114	Vinyl cyclohexene dioxide	1·5303	56·4
115	Methyl α-methylene butyrolactone	1·5118	53·9
116	α-methylene butyrolactone	1·5412	56·4
117	4-dioxolylmethyl methacrylate	1·5084	59·7
118	Methylene-α-valerolactone	1·5431	47·8
119	*o*-methoxy-phenyl metacrylate	1·5705	33·4
120	Isopropyl methacrylate	1·4728	57·9
121	Trifluoroisopropyl methacrylate	1·4177	65·3
122	β-ethoxy-ethyl methacrylate	1·4833	32·0
	Name of Polymer		
123	Condensation resin from di- (*p*-amino-cyclohexyl) methane and sebacic acid	1·5199	52·0
124	Columbia Resin 39	1·5001	58·8

The corresponding values (^{5}, ^{12}) for the relative dispersion are—

Polystyrene	31·0
Polycyclohexyl methacrylate	56·9
Polymethyl methacrylate	57·8

For all three polymers the temperature coefficient is such that the refractive index decreases by 0·00014 for a rise in temperature of 1° C.

It is claimed that of the three polymers only polymethyl methacrylate is affected by absorbed water. The partial dispersion is unchanged but the refractive index may increase by 0·002 when the material is soaked in water for long periods. This effect is likely to be of importance only with refracting elements of high accuracy and having steep contours.

One criticism of plastic glasses which is often voiced is the comparatively high proportion of light which is scattered by the materials. There is, however evidence to support the view that this is not an intrinsic property in that appreciable improvements have already been made by more careful purification of the monomers and by modification of the polymerisation technique[5].

Methods of Manufacture

The established method of glass working can, to a limited extent, be applied to the grinding and polishing of plastics, but the technique is difficult and the low thermal conductivity of the material, together with its mechanical properties, makes it difficullt to achieve either a good figure, or a satisfactory polish, especially on large surfaces.

The two important manufacturing techniques make use of one or other feature of polymers. The first is the deformability at high temperature which permits a mass to be formed to the desired shape by the application of heat and pressure in an optically worked mould. The second method is to fill a mould with monomer, or partially polymerised monomer, and to complete the polymerisation with a catalyst activated by heat or by light. This second method is known as casting.

The moulding is subject to variation. The earliest method to be described involves compression moulding a block of polymer. Refinements can be applied : a rough preform is machined and placed in the press so that during the moulding only a very small quantity of material has to be moved and residual strain is set up only in the surface layers[13]. This technique has been highly developed and products of good accuracy are being obtained. In particular large quantities of spectacle lenses have been made[14].

Injection moulding has also been used extensively[15].

The method of casting has been described in detail[5]. Special precautions are necessary to counteract shrinkage which occurs on polymerisation (10–20% by volume) and one author has described a two-stage process whereby a thin " skin " is cast on to the surface of a moderately accurate preform[16].

Application

The specific properties of plastics thus permit the use of techniques whereby many identical components can be obtained from one optically worked mould. The new applications which are opened up by this possibility are chiefly those where aspheric surfaces would give improved optical performance to instruments which are required in considerable numbers. If the advantage of aspherisation is sufficiently great it will be worth while to tolerate the other shortcomings of the materials, such as surface softness. Light weight and the relative ease with which large components can be made both commend them for some specialised purposes.

The range of optical properties is limited so that the scope of the designer is not as great as with glasses. However, achromatic doublets can be designed and some authors[17] have described the possibilities of athermalising plastic optical systems.

The development of plastic glasses is still in the early stages but already they have been used for a variety of sighting telescopes and other field instruments, particularly for the U.S. services[5]. Other applications include Schmidt systems for television projection[16], [18], [19] and simple magnifiers[10], [21].

The author wishes to acknowledge the very great assistance which has been given him by his colleagues in the preparation of this review.

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DISCUSSION ON NEW OPTICAL MATERIALS

Professor S. S. Ballard stated that a handbook of properties of synthetic crystals had been drawn up by the firm of Baird Associates, Inc., under a contract with the U.S. Army, Engineers, and that much of the new data would shortly be published in the *Journal of the Optical Society of America*. Not only were the optical properties included, but there were also tabulated other properties, particularly mechanical ones, in which he himself was greatly interested.

He drew special attention to the contrasting mechanical properties of lithium fluoride grown *in vacuo* and in air, and also in dry nitrogen. All the specimens exhibited cold flow, but the tensile strength of small bars grown *in vacuo*, as tested in flexure, was greater than that of air-grown specimens in the ratio 3 : 1.

An interesting point was that though the absorption band at about 2.8 microns in the air-grown lithium fluoride is customarily attributed to vibrations of the group H-F-H, the same bands appeared in some samples of lithium fluoride grown in pure dry nitrogen. It should be noted that these are preliminary results, which will bear further investigation.

Dr. A. C. Menzies spoke of the crystals grown by Hilger and Watts. This had its origin in pure research devoted to the second order Raman scattering in alkali halides, and several kinds of pure synthetic salts were wanted. In the course of this, sodium chloride, and the bromides of sodium, potassium, and rubidium had been grown.

This had led to the growing of large crystals (about 9″ across and 6″ deep) of rock salt and potassium bromide for infra-red optics, silver chloride for windows, and potassium iodide and sodium iodide with added thallium, for scintillation counters.

In the course of examining the transmission limits of various materials, Dr. Menzies had noticed a rough rule which connected the approximate infra-red transmission limits with the *reststrahlen*, viz., that this limit was about one-third of the *reststrahlen* wavelength in microns : e.g., for sodium chloride with *reststrahlen* at 52μ, the infra-red transmission limit was about 17μ, while for quartz with *reststrahlen* about 9μ, the limit was at about 3μ. All the materials known to him fitted this rule reasonably well. It could only be a rough rule, and made no pretence of being a law.

Mr. H. C. Rands gave a brief account of the activities of Taylor, Taylor and Hobson, Ltd., in the making of crystals. Satisfactory specimens of sodium chloride and potassium bromide were being grown in 2½″ and 4″ crucibles, and discs 6″ diameter a few inches thick, were obtained from specimens grown in 6½″ diameter crucibles.

Due to impurities in the raw material supplied, progress in the production of good lithium fluoride crystals had been slow. Only by re-crystallisation had it been possible to obtain the comparatively small number of satisfactory discs (up to 1½″ diameter) so far produced. When pure enough raw material became available, it was intended to attempt the growth of larger crystals. (Various samples of crystals were shown in the exhibition.)

Professor Migeotte said that Dr. Normal Wright, of the Dow Chemical Company, had recommended the use of caesium bromide for infra-red optics; it might be able to replace thallium bromo-iodide for transmission in the region of 40-50 microns.

Mr. H. C. Rands asked what was the actual transmission of caesium bromide at a given wavelength for a stated thickness.

Professor S. S. Ballard mentioned silver bromide as an interesting material: a crystal about 1″ in diameter had been grown by the Naval Research Laboratory, Washington.

With regard to low wavelength transmission, pieces of vacuum-grown lithium fluoride has been known to transmit down to nearly 1,000 A. Anyone requiring transmission of low wavelengths must specify *vacuum grown* lithium fluoride, and then the actual limit was a property of the particular piece.

Mr. T. Martin recalled experiments made with plastic optics in binoculars and telescopes during the war. By the end of the war it had been concluded that the plastic materials then available were not sufficiently reliable for use in precision instruments. He asked if this was still the position.

Mr. H. C. Raine in reply referred to work published by the Polaroid Corporation (Reference O.S.R.D. Report No. 4417). Appreciable quantities of instruments using plastic components were made by this Company for use by the United States Services. He agreed, however, that plastic optics were not yet sufficiently well developed for general applications in the most precise instruments.

Mr. W. N. Wheat stated that his firm (Chance Brothers) was making five types of rare-earth optical glasses in melts of up to 8 kilos with larger melts possible in the near future. It was found difficult to remould these glasses into lens blanks without causing crystallisation. Some of the types could not be remoulded at all, others could be softened and pressed into small blanks successfully by exercising great care. Could Mr. Gardner say if all the glasses plotted in his chart could be obtained in large pieces, and could they all be remoulded into lens blanks?

Dr. Gardner (Bureau of Standards) replied that the rare earth glasses are made in platinum crucibles, and the diameter is usually approximately that of the finished lens.

Mr. R. Kingslake (Kodak) said that many of the special glasses could be remoulded, but for economy it was wise to mould directly into the required sizes.

Dr. A. C. Menzies said that Mr. Rand's enquiry was still unanswered; the position was that no one had yet made and tested a piece of caesium bromide. He also had been told of this material by Dr. Norman Wright, and had brought some back to make a crystal and test it. That the transmission in the infra-red of this material would be good was at present pure speculation, based on analogy with similar materials. The *reststrahlen* of caesium bromide were at about 134 microns, so that by the one-third rule the transmission might be expected to be good up to about 45 microns.

Mr. J. W. Perry (Hilger and Watts) thought sodium fluoride a very attractive material, judging by its optical properties so far as known. Its transmission extends from below .2 to beyond 12μ. It appeared to have advantages over fluorite in the optical design of apochromatic lens systems and in infra-red spectroscopy, but more information is needed on its weathering and mechanical properties. Some of the new materials have very attractive optical properties but what Professor Ballard has referred to as the "other properties" would determine their general use by optical designers. In this connection, the compilation which he referred to of all known physical properties, is very welcome, and it is to be hoped this will eventually be published. The claims made for Ultrasil as regards transmission have not been borne out by tests at Hilger and Watts Laboratories on specific samples.

Professor S. S. Ballard said that, roughly speaking, the properties of sodium fluoride appeared intermediate between those of lithium fluoride and sodium chloride, although its refractive index was smaller than that of lithium fluoride. He agreed that the mechanical properties of crystalline materials were very important to optical workers as well as others.

With regard to Ultrasil, he had seen it used with success in front of the 36-power telescope of a stereoscopic rangefinder, which convinced him it must be good for homogeneity.

PROFESSOR R. W. DITCHBURN was primarily interested in obtaining materials which transmitted in the far ultraviolet—some materials which transmitted to 500 A would be ideal. He felt that the most likely material was a fluoride, but not necessarily of lithium. He was willing and anxious to test any materials supplied to him for the purpose, and he would need only a small amount of material—enough to cover a slit a few millimetres high.

He had tested some German fused silica about 1-2 mm. thick, and was surprised to find that the transmission was better than that of crystalline quartz; it let through radiation down to the 1,600-1,700 A range—more like a second quality fluorite than a silica.

With regard to the difference between growing lithium fluoride in air, nitrogen, and vacuo, might the difference be due to the change in temperature distribution brought about by absence of the gas? Alternatively, could it be that something which should diffuse out of the crystal is prevented from doing so by the gas? As a test of these, is the effect worse on the surface of the crystal? Is any difference brought about by holding the material in vacuo for some days, subsequent to growing in air?

PROFESSOR S. S. BALLARD intended to investigate the effect of gas on the growing of lithium fluoride during the coming autumn. He did not believe it was a surface effect, since the absorption was found in pieces cleaved from the middle of a crystal.

DR. R. C. FAUST (British Rayon Research Association) asked if the repetition process employed in making plastic optics could be exploited to make paired objectives for use in such instruments as the Linnik-Zeiss interference microscope?

MR. H. C. RAINE said that this was the type of problem where an accurate process of reproduction from a mould would be ideal. In the casting process the components differ in contour from the mould, but successive castings are very similar. In this specific example of the Linnik-Zeiss interference microscope the required accuracy and stability are of such a very high order that plastic materials are themselves unsuitable.

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